CR 185638 1 c. of 2

# FINAL REPORT

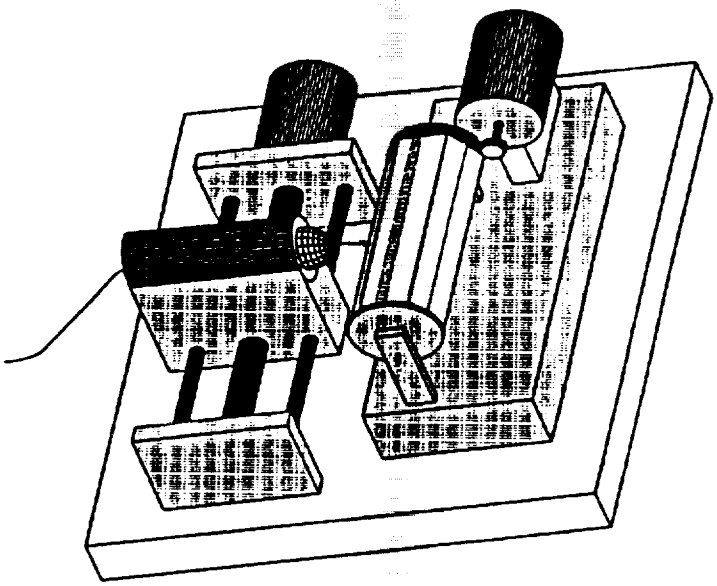
for Contract NAS 9 - 17962

ENTITLED

# LASER WELDING IN SPACE

Principal Investigators:
Gary L. Workman, Ph.D.
and
William F. Kaukler, Ph.D.

submitted to
National Aeronautics and Space Adminstration
Johnson Space Center
Houston, Texas 77058
October 26, 1989



The University of Alabama in Huntsville
Huntsville, Alabama 35899

(NASA-CR-185638) LASER WELDING IN SPACE N91-[illegible]
Final Report (Alabama Univ.) 101 p CSCL 13I

Unclas
G3/37 0019384

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

## EXECUTIVE SUMMARY

Laser welding provides a flexible foundation for assembly, repair and maintenance functions on Space platforms or on other planetary bodies. Flexibility is attained through the ability of the laser beam to interact with practically all materials and through the variety of techniques available to produce and deliver laser power to a workpiece. Although other countries have developed capabilities in the more traditional welding techniques for use in Space, no group has yet developed this dynamic, rapidly evolving technology. The United States can very easily lead the way into this technological advancement.

Most of the lessons learned about the behavior of the welding process in low gravity in this study were obtained by utilization of NASA's KC-135 aircraft. Performing such experiments is extremely beneficial, not only to observe weld phenomena in a simulated microgravity environment; but also to better understand both the physical and chemical processes occuring and the capabilities of the equipment used in the experiments.

The results were not too surprising. Solidification type experiments in microgravity have been performed for many years. The role of convection in such phenomena is fairly well understood. We were surprised; however, to observe convective effects in the small volumes obtained in the laser weld zone. Surface tension driven flows are obviously important as are the surface curvatures and ripples observed after welding. Heat transfer within the weld was affected by acceleration level as indicated by the resulting microstructure changes in low G. All experiments were performed such that both high and low G welds occurred along the same weld beam. Hence we observed effects due to gravity alone.

Our experiments indicate that laser welding in a space environment is feasible and can be safely performed IVA or EVA. Development of the hardware to perform the experiment in a Hitchhiker-g platform is the next step. This experiment provides NASA with an extremely capable technology for routine and emergency welding needs in Space; and the opportunity to once again push the state of the art by putting this technology to work in Space.

We have assessed the resources required to perform this experiment in space, aboard a Shuttle Hitchhiker-g pallet. Over the four year period 1991-94, we recommend that the task will require 13.6 manyears and $ 914,900. In addition to demonstrating the technology and ferreting out the problems encountered, NASA will also have a useful laser materials processing facility for working with both the scientific and the engineering aspects of materials processing in Space.

In the far term we also include several concepts for optimizing available solar power through solar pumping solid state lasers directly for welding power. The concept is not new, only the application. Other NASA engineers and scientists have considered solar pumped lasers for other applications. Our thrust is to provide welding capability, effectively and the solar pumped lasers concepts described in the report provide that capability. The implementation of the concept will obviously not be available until late in the 1990's, *if we begin ground based experimentation now.*

ORIGINAL PAGE
COLOR PHOTOGRAPH

# THE LASER WELDING EXPERIMENT BEING PERFORMED IN LOW GRAVITY

The laser welding aparatus was flown on the KC-135 over 20 times from September, 1988 to June, 1989. Flight procedures were developed to weld through at least one complete parabola to obtain a continuous weld bead reflecting the full variation of gravity between 0.01 and 1.8 G. This mode of operation allowed observation of differences resulting from changes in gravity level only!

# TABLE OF CONTENTS

1.0 BACKGROUND 1

1.1 INTRODUCTION 1

1.2 PREVIOUS WORK 3

1.3 SUPPORTING TECHNOLOGY ADVANCES 10

2.0 OBJECTIVE OF FLIGHT EXPERIMENT 19

2.1 SCOPE OF ACTIVITIES 20

2.2 SPECIFIC OBJECTIVES 22

3.0 FLIGHT EXPERIMENT JUSTIFICATION 24

4.0 POTENTIAL PAYOFFS/BENEFITS OF TECHNOLOGY DEVELOPMENT 27

5.0 INTER-RELATIONSHIPS TO OTHER GROUPS 28

6.0 TECHNICAL DESCRIPTION OF FLIGHT EXPERIMENT 31

7.0 SUPPORTING ANALYSES 38

7.1 KC-135 EXPERIMENTS 38

7.2 KC-135 APPARATUS DESIGN REQUIREMENTS 42

7.3 SPECIMEN ANALYSIS AND METALLOGRAPHY 52

7.4 RESULTS 54

7.5 HEAT FLOW CALCULATIONS 66

7.6 MICRO-HARDNESS 71

7.7 WELD FERRITE IN AUSTENITIC STEEL 77

8.0 OUTLINE FOR FLIGHT DEVELOPMENT 78

9.0 INTIAL ASSESSMENT OF DEVELOPMENT COSTS AND SCHEDULE 79

10.0 SOLAR-PUMPED LASERS 81

11.0 ACKNOWLEDGEMENTS 88

12.0 REFERENCES 90

FIGURES....................................................PAGE

1. REPRESENTATION OF CROSS SECTION OF MELT IN LASER WELDING............5
2. COMPUTED VELOCITY AND TEMPERATURE FIELDS IN A STATIONARY GTA WELD POOL OF 6061 ALUMINUM..................................7
3. TYPICAL SPECTRA SOURCES FOR OPTICAL PUMPING ND:YAG LASERS...........12
4. SPECTRAL CHARACTERISTICS OF CERTAIN METALS AND LASERS...............14
5. COMPARISON OF CONDUCTION LIMITED AND KEYHOLD WELDS..................16
6. SPEED VERSUS PENETRATION FOR SS304 USING PULSED YAG LASERS..........17
7. LASER WELDING DATA FOR SS304 FOR PULSED, CW, AND 30kV EB............18
8. RELATIVE EASE OF FUSION WELDING OF VARIOUS METALS...................30
9. LASER WELDING EXPERIMENT............................................32
10. LASER WELDING EXPERIMENT MOUNTED ON HITCHHIKER-g PLATE..............34
11. LASER WELDING EXPERIMENT WITH FLAT PLATE SAMPLES....................37
12. LASER WELDING EXPERIMENT MOUNTED ON HITCHHIKER-M BRIDGE.............37
13. BREAKOUT OF THE LASER WELDER FLOWN ON THE KC-135....................44
14. VARIOUS VIEWS OF THE KC-135 LASER WELDING EXPERIMENT................46
15. EXPERIMENT INTERCONECTIONS FOR THE KC-135 LASER WELDING EXPERIMENT..47
16. TV CAMERA OPTICS FOR THE KC-135 LASER WELDING EXPERIMENT............48
17. SAMPLE CHAMBER FOR LASER WELDING EXPERIMENT.........................50
18. VACUUM CHAMBER SAMPLE CONFIGURATION FOR KC-135......................51
19. LASER WELDING TRANSLATOR CALIBRATOR.................................53
20. LASER WELDING IN SPACE POST WELD SURFACE STRUCTURE..................57
21. LASER WELDING IN SPACE TRANSVERSE MICROSTRUCTURES T46S2.............58
22. LASER WELDING IN SPACE TRANSVERSE MICROSTRUCTURES T47S3.............59
23. LASER WELDING IN SPACE TRANSVERSE MICROSTRUCTURES T39S1.............60
24. LASER WELDING IN SPACE POST WELD SURFACE STRUCTURE T38S1............63
25. LASER WELDING IN SPACE POST WELD SURFACE STRUCTURE T310S1...........64
26. LASER WELDING IN SPACE TRANSVERSE MICROSTRUCTURES T310S1............65
27. DATA TRACE T39S1....................................................67
28. DATA TRACE T310S1...................................................68
29. DATA TRACE T46S2....................................................69
30. DATA TRACE T46S3....................................................70
31. PENETRATION DATA COMPARISON OF ALUMINUM AND SS304...................72
32. MICROHARDNESS CONVERSION............................................74
33. MICROHARDNESS PROFILE T46S2 LOW-g END...............................75
34. MICROHARDNESS PROFILE T46S2 HIGH-g END..............................76
35. FLIGHT EXPERIMENT SCHEDULE...........................................82
36. SOLAR COLLECTOR EXPERIMENTS..........................................85
37. MULTI-FIBER-LASER CONCEPT...........................................86
38. SOLAR-PUMPED LASER WELDER ON SPACE STATION..........................89

TABLES

I. PERCENT REFLECTANCE..................................................13
II. SPECIMEN SUMMARY....................................................40

# 1.0 BACKGROUND

## 1.1 INTRODUCTION

A new Space Age will begin when the Space Station Freedom is placed into orbit in the 1990's. Our preconceived concepts about the effects of long duration exposure in the space environment on people and facilities will then become a reality. We know that there is a need to transfer certain technologies currently available on Earth to capabilities on orbit to meet the needs of on-orbit repair and maintenance. Evolving from that point in time other technology transfers will occur. Eventually there will be a need to move forward even beyond the orbiting platform. We can anticipate that the ability to perform construction and manufacturing on another planetary body is conceptually possible now and probably achievable during the beginning of the next century.

However, how does one measure the state of technological and engineering ability in order to determine the necessary steps to move forward into these new domains, considering that we have never performed tasks of this magnitude before? What rulers are available for such measurements?

Since, our time in Space has been so short, we have had very little experience with extended durations in Space. For example, the Space Station is to be designed for a 30 year life, yet there are many questions which need to considered in order to select the appropriate materials and construction techniques for a 30 year life in Space. Given the goal of planning for construction, repairing and maintaining of facilities on other planetary bodies, one senses a large defiency in our current depth of knowledge to design and build structures for long term duration outside the earth's terrestrial environment.

It is evident that improving our technological base for performing scientific and engineering tasks in orbital platforms and on other planetary bodies is a necessary step in the progression of activities needed to move planetary exploration forward. For example, ***The Ride Report, Leadership and America's Future in Space***, stated to the NASA Administrator in August, 1987 that NASA ***needs*** to set goals such as **Outpost on the Moon** and **Humans on Mars** in order to maintain momentum in our Space Program and its technological base. The **Report** also recommends that each of these programs use the Space Station platform as a testbed for developing technology and systems for space exploration and as an assembly facility for planetary exploration vehicles. A major incentive for developing technologies for use in Space, as was pointed out in the report, is that ***until advanced technology programs are initiated, the existing goals of human exploration will always remain 10-20 years in the future.***

Obviously, the time to determine which technologies are going to be important for space habitation and exploration is now. The inclusion of materials joining technologies as a necessary capability for Space is also obvious. Construction (assembly), repair, and manufacturing all require joining techniques. Welding has always been the dominant metals joining technique. With the inclusion of composite materials and thermoplastics as structural materials, adhesive joining techniques have begun to play a larger role. At this time; however, reliability of adhesives and composite materials for long term service in Space is still questionable.

To our knowledge, laser welding of metals has not been attempted previously in a microgravity environment. Little information is available about welding in space or in microgravity using any process. More experiments need to be performed to increase our understanding of laser materials processing in microgravity.

## 1.2 PREVIOUS WORK

In ground based activities, there are almost as many welding techniques available as there are materials. Obviously, NASA will not be expected to develop all these techniques for space use. In actuality, only a few techniques will be needed for welding most construction materials encountered in Space structures. Laser welding is obviously the most diverse, being able to work with metals and non-metals alike. Both electron beam (EB) and arc welding processes require that the material being welded be a metal. Electron beam requires a vacuum and arc welding requires an inert gas. Laser beam welding requires neither and can work within either environment. It is probably safe to say that some combination of these three techniques will be part of the tool kit in the Space Station, ready to be used for an emergency repair.

A thorough discussion of the behavior of molten materials and solidification phenomena was presented in the proposal for this work being reported. We repeat some of the discussion here.

Temperature distribution within the weld pool and the circulation of the melt within the pool will affect the final weld microstructure and composition. Figures 1a and 1b, taken from Anthony and Cline[1] shows an example of how convection flows distribute the molten metal in a weld. Surface tension driven convection is the major fluid driving force in laser welding[3]. Most models for weld pool shapes (example: any by Mazumder et. al.[3] or Kou et. al.[6]) assume that the weld pool surface is flat and coplanar with the parent metal surface. This trend is changing with the work by Zacharia et al[8,9] where a program called WELDER can model the free surface liquid pool shape and the contributory flows underneath. In another paper, by Lin and Eager[5], the claim is that a vortex forms within the weld pool at the arc centerline that depresses the surface. Toroidal flow of liquid was assumed to occur from electromagnetic and surface tension driven flow from the high (300A) current used.

The overall weld pool temperature is lowered by increasing convection rates[4]. This lower temperature of the melt helps keep dendrite fragments in suspension without remelting. This keeps grain size down and more equiaxed in the fusion zone. Greater convection rates are expected when buoyancy effects contribute to surface tension gradient driven flows. Convec-

# FIGURE 1.

## REPRESENTATION OF CROSS SECTION OF MELT POOL IN LASER WELDING

Figure 1A. Representation of melt pool during laser welding.

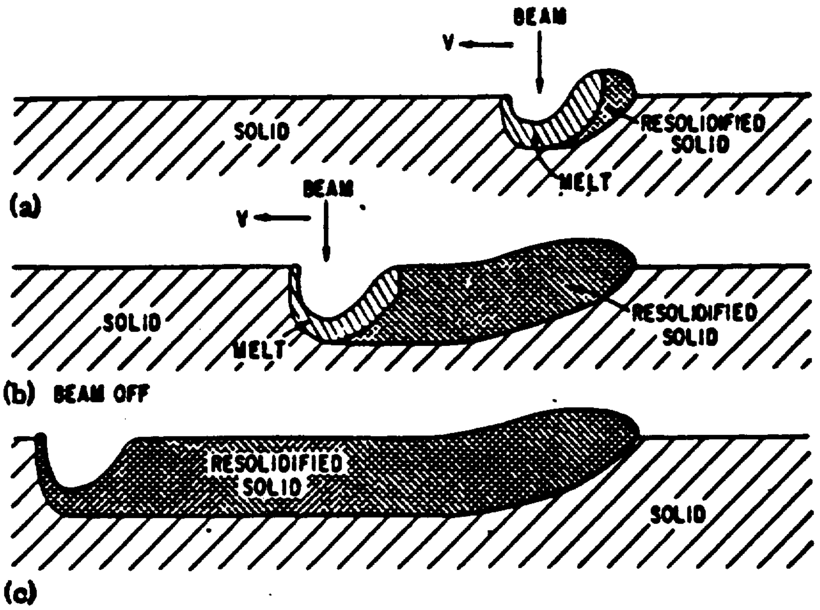
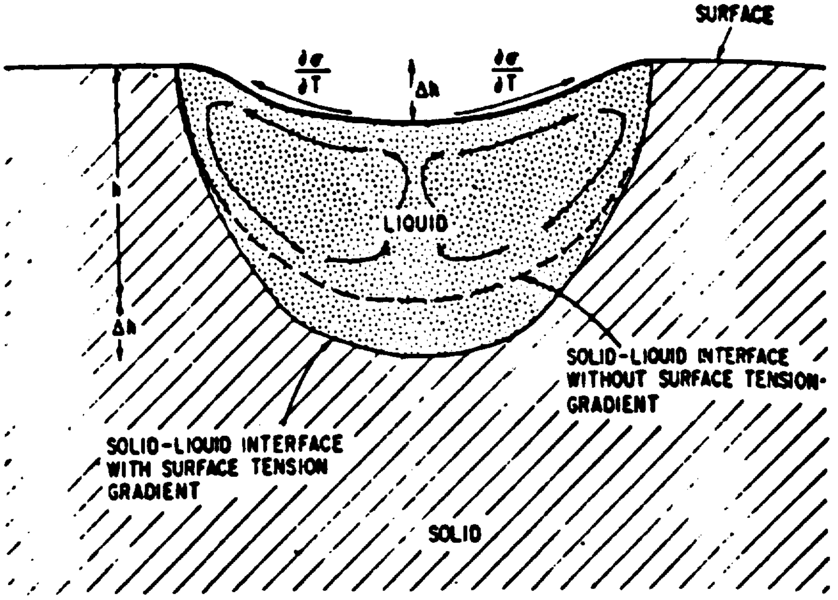

BEAM
V
SOLID
RESOLIDIFIED SOLID
MELT
(a)
BEAM
V
SOLID
MELT
RESOLIDIFIED SOLID
(b) BEAM OFF
RESOLIDIFIED SOLID
SOLID
(c)

Figure 1B. A cross section perpendicular to the laser beam path through the melt pool in the steady–state regime of the above figure.


SURFACE
$\frac{\partial\sigma}{\partial T}$
$\Delta h$
$\frac{\partial\sigma}{\partial T}$
h
$\Delta h$
LIQUID
SOLID-LIQUID INTERFACE WITHOUT SURFACE TENSION GRADIENT
SOLID-LIQUID INTERFACE WITH SURFACE TENSION GRADIENT
SOLID

tive flows across the solid-liquid interface in the pool will control the rate and quality of freezing. Since stainless steel has a strong negative surface tension temperature coefficient, heat from the laser spot will be transported to the edges of the pool across the surface, as shown in Figure 1b. Natural convection due to buoyancy effects from hotter melts being less dense than cooler melts contribute to heat transfer when accelerations (gravity) are significant. Buoyancy driven flow adds to the surface tension driven flow if the temperature coefficient of surface tension is negative. This flow mechanism is non-existent in a microgravity environment.

Electric fields from arc or plasma or EB methods induce magneto-hydrodynamic convective flows that are superposed with the surface tension driven flows. The results from computing velocity and temperature fields in a stationary GTA weld pool of 6061 aluminum[6] are given in Figure 2. At moderate currents of 150 amps or less, surface tension driven flows can dominate electromagnetically caused flows in arc welds[3]. With the thin-sectioned space structure materials, such low currents would be the normal amount if arc welding. Changes in the flows caused by microgravity need to be studied since the weld pool will be of significant size relative to the metal thickness. All metallurgical aspects of the weld are affected. The size and shape of the HAZ, the surface character of the weld bead, and the solidification structures of the fusion zone will all be influenced by the heat transfer changes. Changes in convective flow affect porosity, can lead to lack of fusion, and may lead to

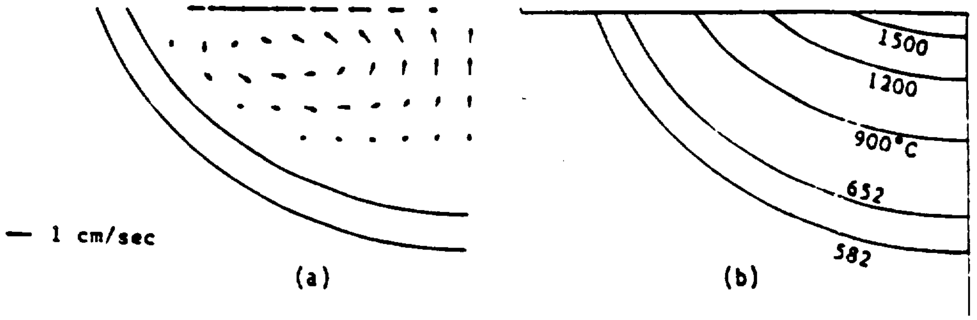
## FIGURE 2.

Computed Velocity and Temperature Fields in
a Stationary GTA Weld Pool of 6061 Aluminum

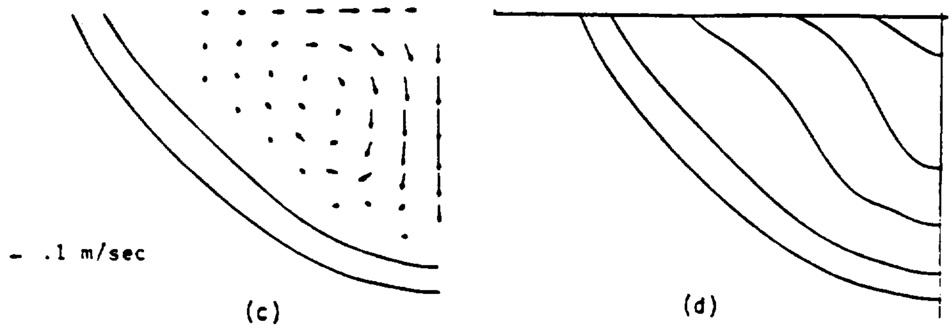
(a), (c), and (e) represent velocity fields
(b), (d) and (f) represent temperature fields
The magnitudes of velocities are represented by the lengths
of the arrows. From Kou and Sun.

VELOCITY FIELD TEMPERATURE FIELD

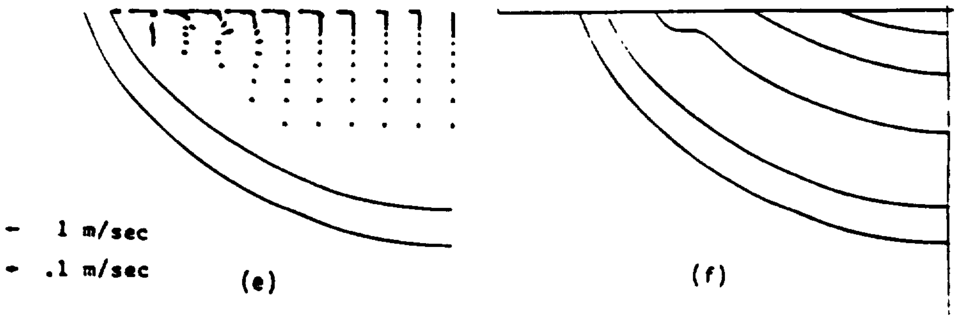
Buoyancy Force


1500
1200
900°C
652
582
1 cm/sec
(a)
(b)

Electromagnetic Force



Surface Tension


1 m/sec
.1 m/sec
(e)
(f)

variable penetration along the weld bead. Weld conditions for the process in space may need to be modified to make sound welds. In fact, we believe the process will be better when done in space.

The work performed under this effort utilized the KC-135 as a low gravity simulator for studying the effect of gravity on laser welds. Section 7 of this report will present the results of these experiments. Even with the small volume of the heat effected zone (HAZ) resulting from the laser heat source, we were able to observe differences in solidification in high G versus low G. The impact of these differences in microstructure on the service requirements of structural materials has never been considered, much less studied. Only one welding experiment has been manifested by NASA in previous years.[10] The results of that experiment were never fully analyzed in terms of the value of the process (EB welding) as a construction or repair process in microgravity. The observed metallurgical differences as compared to ground based samples were not fully described in the report. Comparisons of results obtained from their KC-135 experiments and with the laser welding system we flew on the KC-135 are also difficult, since they apparently were not able to process any samples in low gravity on the KC-135.

It is well known throughout the aerospace community that the Soviets have flown numerous welding experiments in Space. We have been able to obtain only one paper which reports on the results of their experiments.[11] It was a translation of a historical document that presents many interesting perspectives of the

Soviet's work in Space welding. The most interesting part of the paper was the historical information defining their space experiments beginning in 1965 with 25-30 seconds of low gravity on the Tu-104 aircaraft. These experiments were performed in preparation for the first space experiment, which occurred in 1969 with the 'Vulkan' device. It is interesting that the Soviets performed a series of experiments on their parabolic aircraft in order to define which welding experiments would be the most useful for Space. They also indicated that the extended microgravity time in Space required some additional experimental adjustments for both manual and automated welding.

Metallurgical features of samples welded in Space were described as having greater porosity, 30 to 40% increase in strength of welds on stainless steel and titanium alloys with simultaneous refinement of the metal structure. They also state "*obviously these effects are connected with the peculiarities of crystallization of the metal during welding in weightlessness*". Another observation reported was the lack of burn-through in the absence of gravity, resulting in easier welding of thin materials. The explanation was described in terms of the greatly increased influence of capillary effects in weightlessness.

The only other data we have available on the effects of gravity on welding processes is that obtained in the series of KC-135 flights performed under this contract. Since both of the principal investigators in this study have several years experience in studying the effects of microgravity on solidification phenomena, we were able to apply many of the lessons learned from previous work in performing such experiments.

## 1.3 SUPPORTING TECHNOLOGY ADVANCES

Tremendous advances have been made during the past year in several technologies which will benefit laser welding in Space. A number of major milestones in improvements in efficiency, power, diversity in pump sources, fiber optical coupling techniques, and overall capabilities of solid state lasers for materials processing applications have been achieved. The continued growth in technological advances in solid state lasers is fueled by a number of commercial interests. Space applications of these systems can benefit from these advances without having to push the technology for its own reasons. On the other hand solar pumped applications will predominantly benefit space applications and for that reason, this technology will probably only mature after NASA once again takes a lead in its development. Earlier developments pursued by NASA for solar pumped lasers apparently were pre-mature. The laser devices, as well as our understanding of how to integrate these systems, are much more sophisticated today than they were 10 years ago.

Among the technological advances in the solid-state laser, which will assist in determining the design of the space experiment, include the laser pumping system and the laser beam delivery system. Key ingredients for laser pumping a Nd:YAG laser are overlapping wavelengths between the pump source and the optimal absorption region of the $Nd^{+++}$ ions in the YAG matrix.

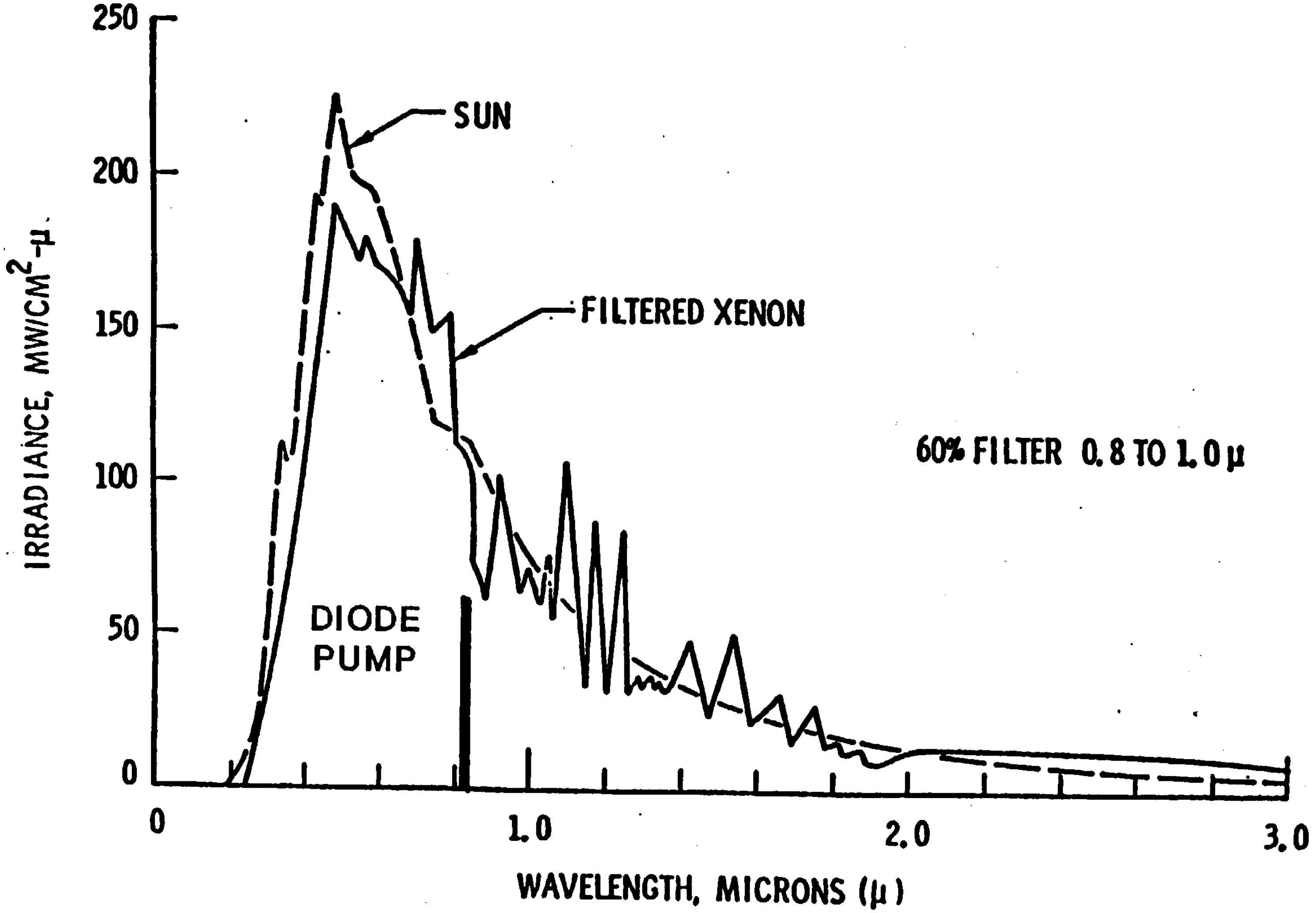
Figure 3 illustrates the spectral characteristics associated with pumping sources for Nd-YAG lasers. The primary requirement for pumping lasers is to use an excitation wavelength shorter than the output wavelength of the laser, which is at 1.06 microns for the Nd-YAG. As seen in Figure 3., the diode pump emits a wavelength that is higher in energy than the Nd-YAG and overlapping the absorption region. The diode pump is a recent innovation, enabling lower power levels to be used, due to the increased efficiency of conversion from pump energy to laser output energy.

The per cent reflection of the laser light of several selected materials at several characteristic wavelengths is given in Table 1. A higher per cent reflectivity indicates less coupling of the laser energy into the part being welded. Figure 4 shows more clearly the comparison of the per cent reflectivity of several metals at the output wavelength of the $CO_2$ laser at 10.6 microns with that of the Nd:YAG at 1.06 microns. This graph indicates that for structural metals, in particular, the 1.06 micron wavelength is less reflective, resulting in an overall improved coupling efficiency.

A feature of the Shuttle experiment design which will need some explanation is the change in welding mode from conduction limited as was performed in the KC-135 experiments to keyhole mode for the Shuttle experiments. The increased depth of penetration in comparison with the amount of energy imparted to the workpiece also implies an increase in the overall efficiency of the process. The primary impact on the experiment is then that

FIGURE 3.

TYPICAL SPECTRA OF SOURCES
FOR OPTICAL PUMPING OF ND:YAG LASERS



# Percent Reflectance of Metals at Given Wavelengths of Common Lasers

Wavelength, µm

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $CO_2$<br>10.6 | 97% | 90% | 99% | 98% | 99% | 99% | 98% | 97% |
| Nd:YAG<br>1.06 | 64% | 65% | 98% | 97% | 99% | 96% | 83% | 75% |
| Ruby<br>.6943 | 57% | 57% | 95% | 95% | 98% | 90% | 90% | 69% |
| HeNe<br>.633 | 56% | 56% | 94% | 93% | 96% | 91% | 79% | 67% |
| | Fe | SS304 | Ag | Cu | Au | Al | Rh | Pt |

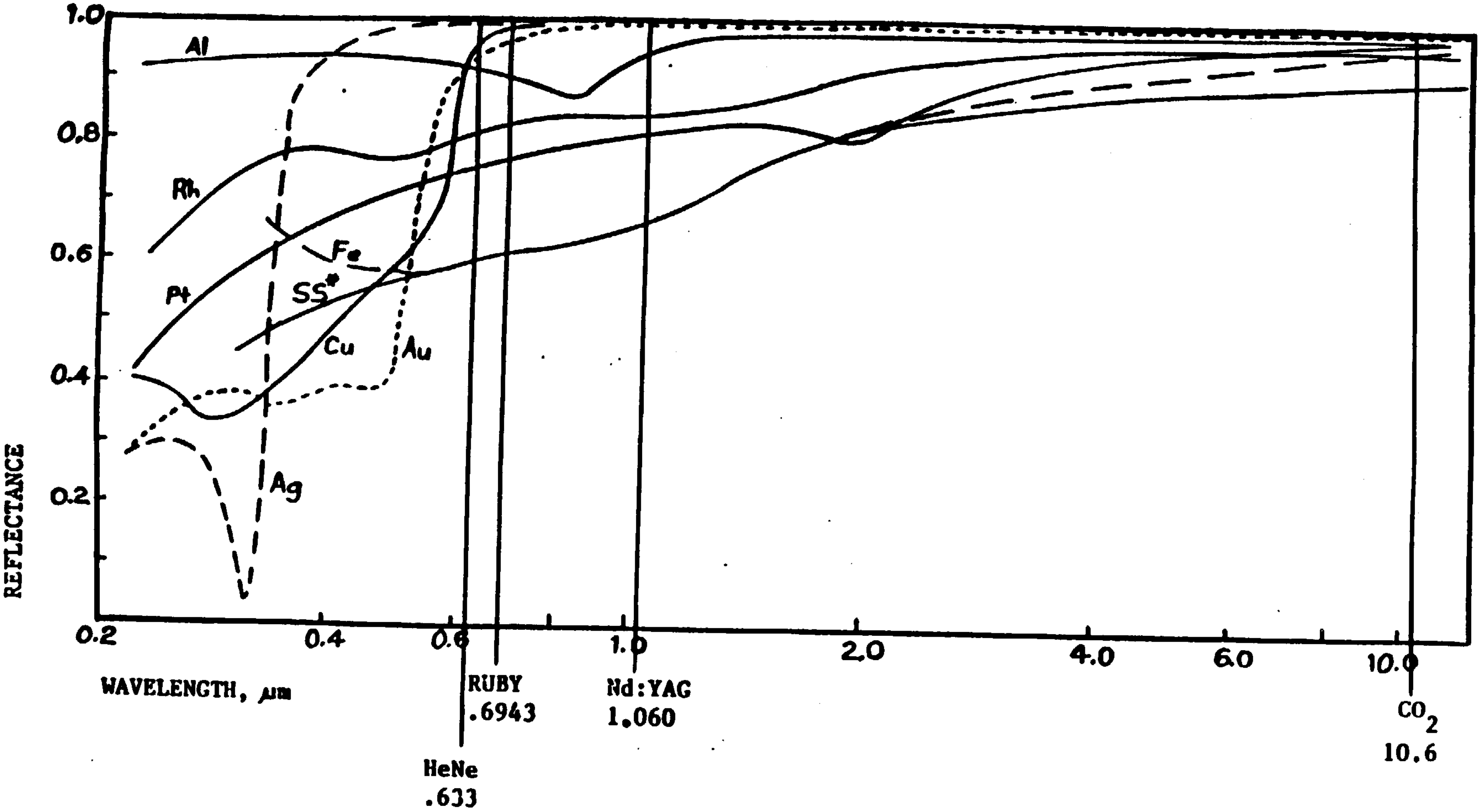
Metals

**TABLE 1.**

Weast, Robert C. PhD., CRC Handbook of Chemistry and Physics, 66 Ed.
CRC Press, Boca Raton, FL p. E375–E389

# FIGURE 4.

## SPECTRAL CHARACTERISTICS OF CERTAIN METALS AND LASERS



* Stainless Steel

Driscoll, Walter G. (1978), Handbook of Optics, Optical Society of America McGraw-Hill Book Co. St. Louis, p8-92.

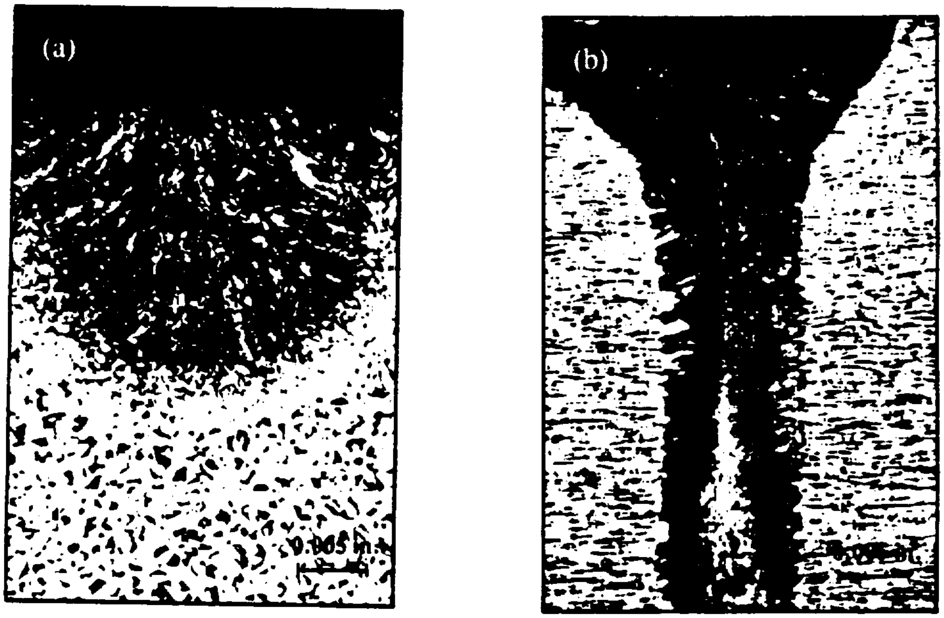
the welding is performed by a series of pulses, rather than continuously as in the CW mode of operation. Examples of welds using the two modes of operation are given in Figure 5, which is taken from reference material published by Laserdyne, Inc.. The pulsed mode of operation does result in deeper penetration, a smaller heat affected zone, and lower overall energy requirements. All factors represent favorable attributes for welding in space. The weld speed is then determined by the pulse rate of the laser energy. Figures 6 and 7, indicate the relationships occurring between power, speed, and mode of welding.[11] Note that in Figure 7, the close proximity of the parameters for the pulsed laser to those for the 30 kV electron beam.

There is a need to construct stiff, lightweight, and long-lived structures for the extendible portions of Space station. With all the available materials, the lightweight and long-lived aspects are easily satisfied. It is by using metal components and welding the joints that one can achieve the stiffest and most rigid structures. Alternate concepts include lock-rings, crimped fittings, flanges of various types and adhesives. None of these joining methods will produce as reliable a joint as a simple weld. These joining methods all add weight at the joints that raise the inertial mass of the structure and thereby increase the stresses on the anchor points of

# FIGURE 5.

# COMPARISON OF CONDUCTION LIMITED AND KEYHOLE WELDS

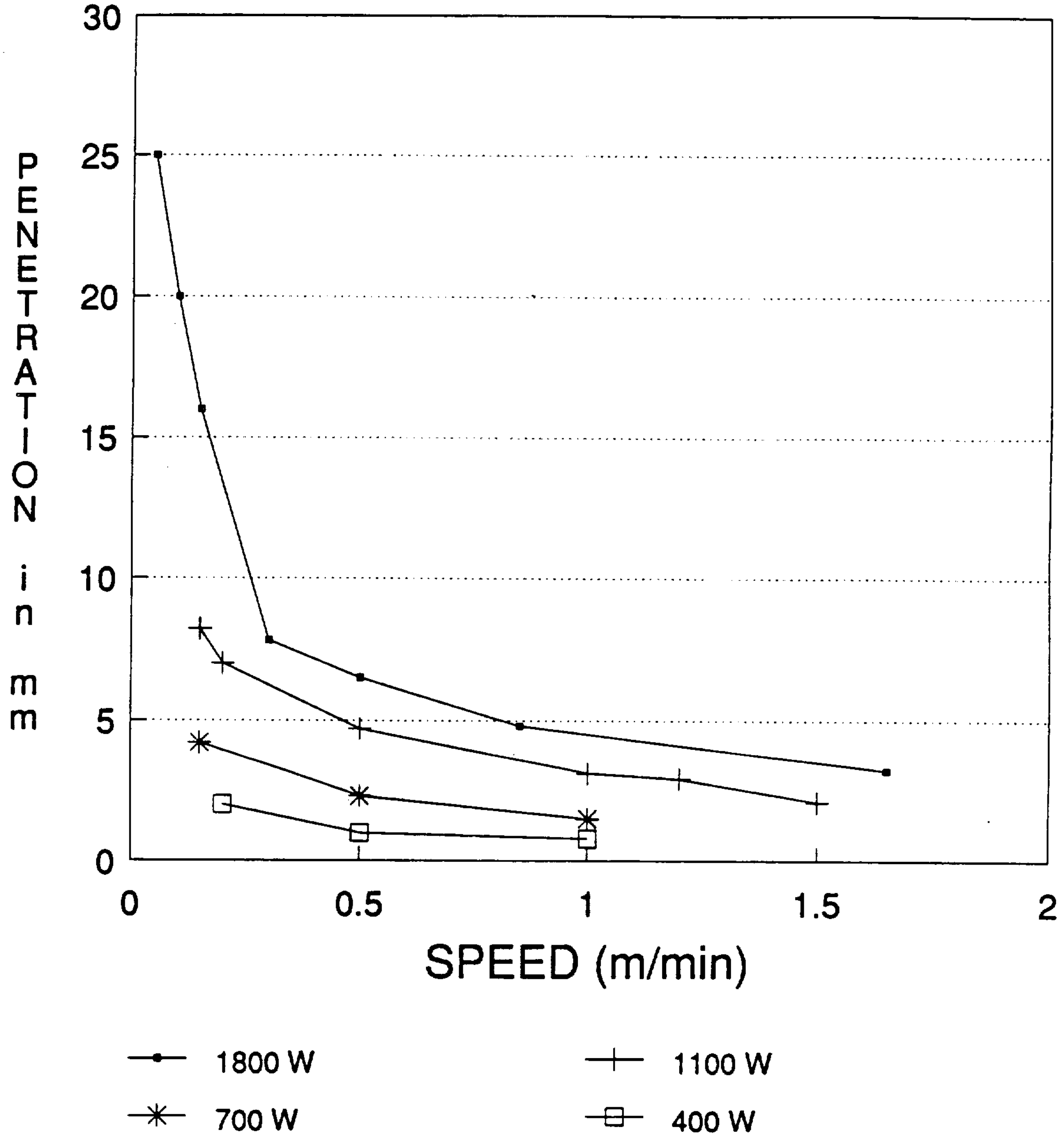
These two micrographs show typical crossections of laser welds in stainless steel 304. Conduction limited mode is displayed in (a); while pulsed mode can produce keyholing holing leading to crossections displayed in (b).



Ref. Laserdyne, Inc.

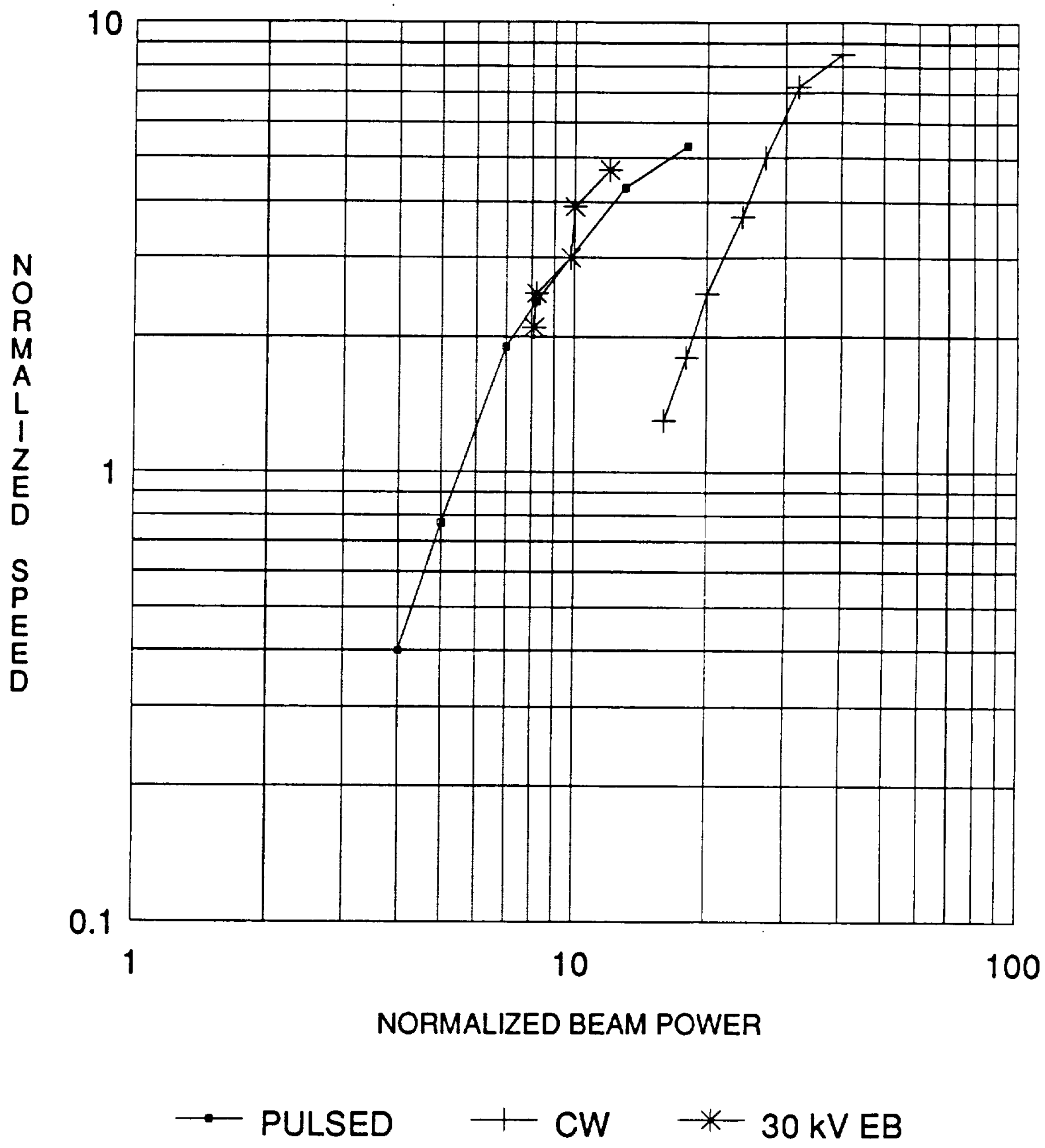
# FIGURE 6.

## SPEED VERSUS PENETRATION FOR SS304 USING PULSED YAG LASERS



# FIGURE 7.

## LASER WELDING DATA FOR SS304 FOR PULSED, CW, AND 30kV EB



the structure since it will undergo minor maneuvers in orbit.

Infusible events can cause damage to the station structure and require repair. Regardless of the materials selected laser welding of the repair can be performed. One could simply fill in small holes formed by meteorites by laser melting a plug of the same material in place. Metals, ceramics and polymers can all be melted by laser processing.

## 2.0 OBJECTIVE OF FLIGHT EXPERIMENT

The objective of this proposed activity is to perform laser welding experiments with different materials in the space environment using experimental apparatus specially constructed for the Shuttle and return the apparatus and samples to earth for analysis. Beginning with a completely automated welding experiment, the goal will be to develop welding procedures for different materials and to gradually increase the involvement of the flight crew to determine the capability of humans to assemble and repair structures in Space using laser welding techniques.

The major experimental parameters for the Shuttle experiment are the extended microgravity, the hard vacuum of space, and human factors. One needs to know if welds in space are worse or better than on the ground and by how much. As the Soviet's work has indicated, repair methods will certainly need modification to accommodate space conditions. Due to severe power constraints and cooling requirements, Q-switching of the laser will be introduced.

Engineering concepts for the laser welding facility need to be tested by Space flight. Critical components and conditions need evaluation and verification. Use of the laser in close proximity to the work area requires a different philosophy from using a laser as a space weapon or for communications in space. In the planned experiment, a fiber optic delivery system will be used to bring the laser power safely to the workpiece. The advantages are clear, but the space environment may bring out disadvantages not otherwise anticipated.

A number of technological developments will be demonstrated in the implementation of the Shuttle laser welding system:

a. to implement a laser system that can melt metal within available resources.

b. power dissipation from the laser and the specimen.

c. develop pulsed modes for use in microgravity and see if plasma becomes a problem in high vacuum and low gravity.

d. engineering design of a flight qualified laser with emphasis on pumping methods and heat transfer in the Shuttle environment.

## 2.1 SCOPE OF ACTIVITIES

Since the initial phases of this project began, it has become clear that many different materials can be processed in the proposed laser welding facility. The list of materials is very broad, because the range of materials which can be welded by lasers is very broad. A design goal of this experiment is to enable a number of different materials to be processed; thereby, expanding the scope of its experimental utility and expanding the number of scientific and engineering investigators who can participate and benefit from its availablity. We have already had a number of conversations with other researchers who would be interested in participating in a space-based laser welding capability.

As was recognized at **INSTEP 88**, welding is a materials processing discipline. The information obtained from such experiments can be applied to engineering materials or to provide a scientific foundation for understanding how materials do join, both in 0 G as well as in 1 G.

The laser welding experiment will be constructed to accomodate the processing of many different materials, allowing many investigators to participate in the experiments. The system as designed will capable of performing studies of weld processes for different materials and for the development of procedures to perform laser welding on particular materials of interest to engineering organizations. The experimental apparatus will be an assembly to weld either tubes of different thicknesses circumferentially and types of materials and/or flat specimens, also of varying thicknesses and compositions.

Evolving through a progression of laser welding capabilities in Space, it is even appropriate to begin developing concepts for a space-based laser welding facility which is pumped by solar radiation; thereby, becoming without a doubt, the welding technology with the lowest power requirements of all the currently conceived approaches for space. For Space Station to achieve IOC, such a capability is not only affordable, but certainly it also represents a concept which is simple to implement.

At a later time, we intend to test a solar pumped laser device for future use as a welding system. Or, if it is more feasible, to use concentrated solar energy to directly preheat the weldment and reduce power requirements for the laser. This way, the laser can still produce a minimal weld volume and HAZ. The need for preheat arises when accounting for the likely frigid temperatures the structure may have when in space. Our research has found that over 95% of the heat needed to weld is used to raise the metal temperature to melting from ambient. Many have suggested that concentrated solar energy be used to weld and bypass laser conversion. While the concept would be possible and could be less complex, the fact remains that only monochromatic and coherent light from a laser can be focused to a small enough point to obtain the nearly infinitely high temperatures necessary to form small weld beads with small heat affected zones. Since high weld strength is characterized by minimal HAZ's and rapid solidification, welding by laser admirably offers these performance characteristics. A number of intriguing scenarios are possible with the solar pumped laser welding facility for the Space Station.

## 2.3 SPECIFIC OBJECTIVES

Briefly, the need to perform the experiment in Space will be to verify and expand upon the results obtained from the KC-135 experiments and to verify the engineering design of the laser welding facility focusing on these critical components for operation in Space:

1) Diode pumped laser system
2) Q-switching devices
3) Power supply
4) Cooling system
5) Fiber optic delivery system

and to analyze the results from laser welding in space by:

1) Microstructural examination, as in the past.
2) Analyzing pulsed operation of the laser.
3) Testing the welds for strength in comparison to 1 G.
4) Measuring material losses from melting in hard vacuum.

As a result of our research, the number of unknowns regarding welding in space has been minimized. Our experiments have shown differences in the microstructure of a weld when welding in a low G environment. Secondly, in the Shuttle experiment, a true space vacuum can be achieved without the need for enclosing the weldment in a chamber. For our experiments, in order to simulate space vacuum, we have had to pass the laser beam through a window and suffer relatively poor vacuum conditions. We are following the proper course of action for the development of a flight experiment:

1) test the experiment on the ground,
2) then test the experiment on the KC-135
3) and then with this experience, design a true space experiment for the Shuttle.

It is interesting to note that the Soviets followed this line of thought in the 1960's. The U.S. program seems to be several decades late in this mode of thinking.

## 3. FLIGHT EXPERIMENT JUSTIFICATION

The logical experiment to follow the experiments flown on the KC-135 is to develop a Shuttle experiment for laser welding in Space. Even the Soviets noted that equipment and processes had to be modified to operate in Space, even after succesful operation in parabolic aircraft experiments. However, the time and money spent in these modifications are much less than in making the jump from ground-based experimentation to Space. Also there is a difference between $10^{-2}$ G and $1o^{-6}$ G in terms of the microstructure observed upon solidification; a well debated issue in the Materials Processing in Space community. The results achieved on the KC-135 can only promote interest to extend the experiments into Space.

Structural benefits will be provided by using the small weld volumes offered by laser melting. Similarly small heat affected zones will minimize degradation of material strength caused by the welding process. In this work, the effect microgravity has on the shape of the weld pool and the resulting changes to the heat transfer conditions are being investigated.

The use of laser light for heating and a flexible beam delivery system will give considerably greater flexibility over other methods. NASA should be interested in laser welding methods because of the following disadvantages of the other methods:

1) Although they are electrical heat sources, plasma or arc welding requires that a supply of consumable special gases be available. These requirements impacts logistics of supply and design for storage. Also contamination of the environment with gaseous debris will become more probable unless extreme care is taken in the design of the welding apparatus. Scientific experiments, particularly the ones which use the Space Station as a scientific observation platform will be severely impacted by such contamination.

2) Short (less than 20 feet) electrical connections need to be made for circuit completion for EB or arc welding apparatus, in order to avoid power loss due to voltage drops.

3) High accelerating voltages are used for EB or arc methods that could affect sensitive instruments in the vicinity or impact the electromagnetic environment of the Space Station.

4) There is a danger of X-Radiation from EB apparatus, impacting requirements for safety consideration for weld operations.

5) EB welding requires a vacuum and the arc torches will be designed for operation in a vacuum thus precluding their use in the habitable environment.

6) Only metals can be joined by EB or arc.

7) Either method consumes considerable power and can only

be provided by electrical connections at specific locations on Space Station.

8) In emergencies, electrical power may not be available to run EB or arc.

9) With plasma or arc methods, weld bead and HAZ dimensions are far greater than with laser or EB. A larger volume of metal is melted and so solidification is slowed.

Clear advantages of the laser welding technique are that with a fiber optic delivery system one could bring the laser power safely into the habitable environment or into a vessel or chamber that otherwise would not permit a larger welding device to be introduced. Multiple sources can also be combined for increased output power. The fiber optic can easily be gripped by a robot arm and allow remote welding or automated welding by laser. The length of the fiber optic cable can exceed 100 feet or better without a loss in output power. Output power can also be controlled and safety devices attached to prevent accidental exposure.

The logical path to implementation of a space-based welding facility appears to be a two step process consisting of two experiments. One, is to perform laser melting experiments on the Shuttle that will simulate welding procedures on Space Station using a fiber-optic delivered Nd-YAG laser beam. The second, is to fly a solar pumped laser with its own concentrator system. Since it is our contention that all power for welding must ultimately come from the sun, a solar-powered laser would reduce the load on the already overloaded Space Station power grid. A solar concentrator for power collection has not been flown in space. Other research groups, including groups within NASA, are interested in developing a solar concentrator power conversion system to fly for other purposes. Our interest is to prepare to have a sun-powered welder available for Space structure assembly, and not just for repair.

A Shuttle experiment will have two aspects: verification of technique and studying space effects on laser welding. The experiment would not be "to see if one could weld in space". It is understood that one can. Experiments on the KC-135 show welding materials in microgravity can be done with a laser. In addition to our work, Duley et al[16] have welded plastics with a $CO_2$ laser on the KC-135. This experience base leads us to the conclusion that various materials can be welded in space with a laser.

## 4. POTENTIAL PAYOFFS/BENEFITS OF TECHNOLOGY DEVELOPMENT

As mentioned in previous sections, the NASA is embarking on a number of activities in Space which will require welding of materials. In order for these activities to be cost effective, as well as successful, we need to develop the following:

a. Ability to assemble and repair structures in Space.
b. An experimental facility for improving our understanding of weld processes.
c. Improved efficiencies in diode pumped and solar pumped laser systems.

The payoffs are then reflected in two ways. Successful space programs that generate interest and enthusiasm to enhance the role of the US in Space and in the technology transfer to other government and industrial programs that normally evolves from successfully implemented NASA programs.

## 5. INTER-RELATIONSHIPS TO OTHER GROUPS

The welding research community includes aerospace, nuclear, and university groups who either seek to improve the welding of unique materials or perform experiments to better understand the metallurgical processes occurring during welding. A microgravity laser welding facility provides a unique platform for this research community. Eliminating bouyancy and convection forces due to gravity simplifies the theoretical basis for the process.

Several recent publications describe other NASA programs which impact the laser design proposed for the laser welding facility. NASA has already chosen solid state lasers for future remote sensing systems[13] and deep space communcations[14]. In a more recent article, the space qualification of of a Nd-YAG laser and associated reliability concepts are presented.[15] The experience of these groups in working on space qualifying solid state lasers for NASA programs will be applied to the design of the laser welding facility.

Materials research groups have performed many studies on metal fusion in order to determine which elements will fuse, thereby being 'weldable'. Although the material is a bit dated at this time, Cohen[16] gives an excellent summary of laser materials processing. In that article he reproduces a chart first published by Irving[17] and is partially reproduced in Figure 8. Examples of metal combinations which are of interest to researchers in laser welding are presented in a matrix format and represent a suitable place to start in defining useful experiments for space. Obviously, the more common weldable combinations can still provide interesting and sometimes beneficial microstructure when welded in Space, although the most interesting experiments should be those experimenting with metal combinations which are not compatible on Earth, but may be compatible in Space.

We also anticipate that having such a Space Laser Welding Facility available for researchers participating in welding experiments will provide NASA with a strong cadre of welding experts available for future projects or programs.

# FIGURE 8.

## RELATIVE EASE OF FUSION WELDING OF VARIOUS METALS

- ● Easily Weldable
- ○ Weldable
- c Weld with Caution
- ☐ Undesirable Combinations

Column elements are listed in italics.

| | *Antimony* | *Aluminum* | *Gold* | *Beryllium* | *Cadmium* | *Cobalt* | *Chromium* | *Copper* | *Iron* | *Magnesium* | *Manganese* | *Molybdenum* | *Columbium* | *Nickel* | *Lead* | *Platinum* | *Rhenium* | *Tin* | *Tantalum* | *Titanium* | *Vanadium* | *Tungsten* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminum** | ○ | | | | | | | | | | | | | | | | | | | | | |
| **Gold** | ● | | | | | | | | | | | | | | | | | | | | | |
| **Beryllium** | | ○ | | | | | | | | | | | | | | | | | | | | |
| **Cadmium** | | | | | | | | | | | | | | | | | | | | | | |
| **Cobalt** | c | ○ | ○ | | c | | | | | | | | | | | | | | | | | |
| **Chromium** | ○ | | c | | c | ○ | | | | | | | | | | | | | | | | |
| **Copper** | ○ | | ● | | | ○ | ○ | | | | | | | | | | | | | | | |
| **Iron** | c | | ○ | | c | ○ | ○ | ○ | | | | | | | | | | | | | | |
| **Magnesium** | | ○ | | | ● | | | | | | | | | | | | | | | | | |
| **Mangenese** | ○ | | | | c | ○ | ○ | ● | ○ | | | | | | | | | | | | | |
| **Molybdenum** | c | | ○ | | | | ● | c | ○ | c | c | | | | | | | | | | | |
| **Columbium** | | | | | | | | ○ | | | | ● | | | | | | | | | | |
| **Nickel** | ○ | | | | c | ● | ○ | ● | ○ | | ○ | | | | | | | | | | | |
| **Lead** | ○ | | | | ○ | ○ | ○ | | ○ | | ○ | c | | ○ | | | | | | | | |
| **Platinum** | ● | | ● | | | ● | ○ | ● | ● | | | ○ | | ● | | | | | | | | |
| **Rhenium** | c | | | | | ● | ● | | | | | | | c | | ○ | | | | | | |
| **Tin** | ○ | | | c | ○ | | ○ | ○ | | | | c | | | ○ | | | | | | | |
| **Tantalum** | | | | | | | | | | | | ● | ● | | | | | | | | | |
| **Titanium** | ○ | | | | | | ● | | | c | | ● | ● | | | | | | ● | | | |
| **Vanadium** | c | | c | | | | | | ● | | | ● | ● | | | | | | | ● | | |
| **Tungsten** | c | | | | | | | ● | | c | c | ● | ● | | c | ● | | | ● | ○ | ● | |
| **Zirconium** | | | | | c | | | | | c | | | ● | | | | | | ○ | ● | | |

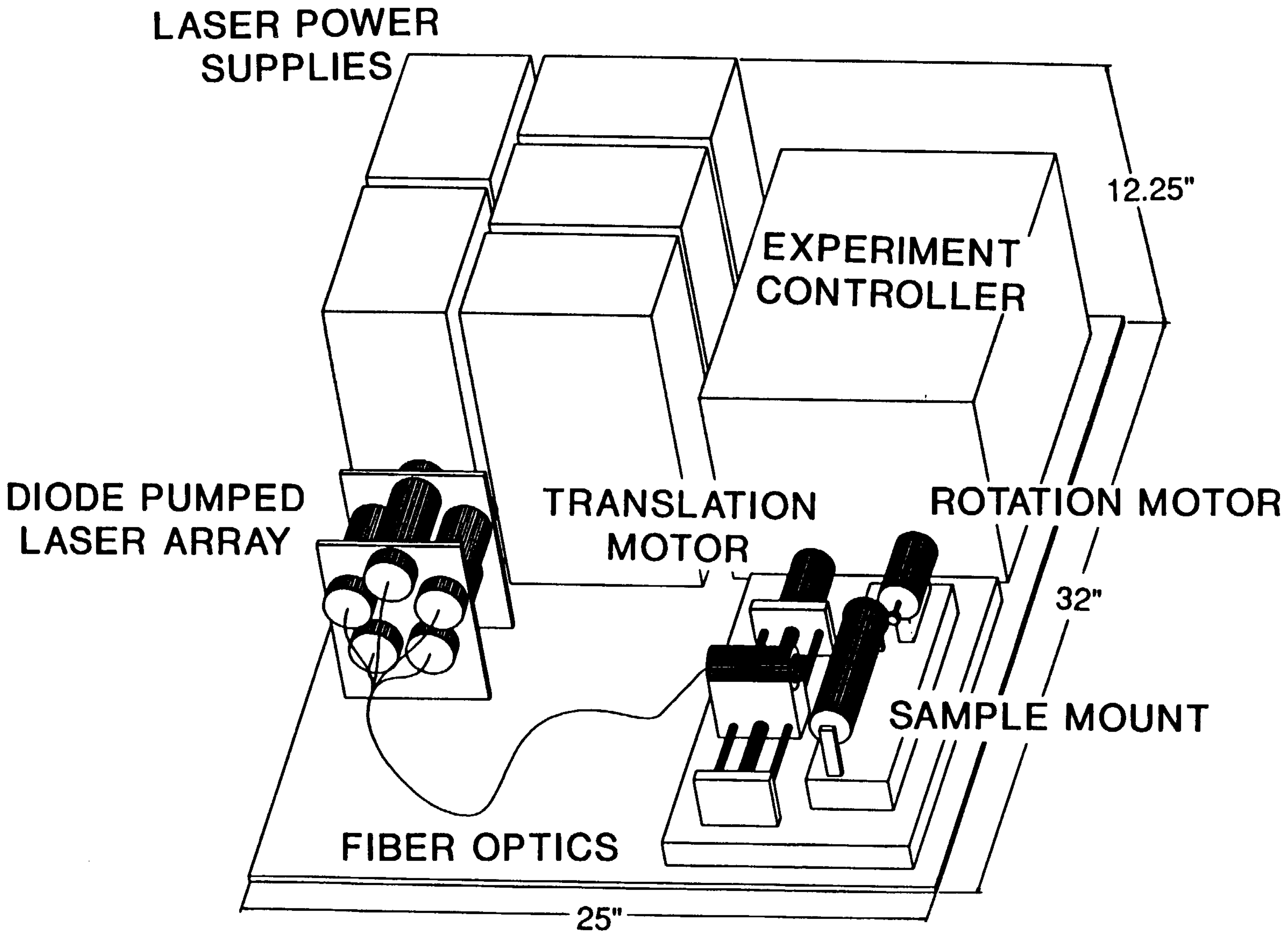
## 6.0 TECHNICAL DESCRIPTION OF FLIGHT EXPERIMENT

The rapidly changing technologies in today's laser materials processing industry creates several problems in defining the components for a space experiment which will not fly for several years. For the purposes of this report we have chosen to present the most probable configuration of a laser welding module, using the state-of-the art capabilities commercially available today. The caveat to remember is that we will be able to simplify the system, once we are able to characterize the capabilities of pulsed welding on KC-135 experiments. These experiments are needed to determine the actual power requirements for welding in microgravity using a diode pumped laser system.

Figure 9 is a schematic diagram of the proposed experiment as it stands at this time. In this representation of the experimental apparatus, the laser energy will come from a bank of Q-switched diode pumped Nd-YAG lasers. These represent the latest technology in solid-state lasers, as well as the most conservative in power requirements. In this drawing, the laser source is represented by a bank of five diode-pumped lasers transmitting laser energy into five optical fibers which will then steer the exit beams to a single, common fiber. A focussing system concentrates the output of the fiber onto the weldment surface. The working end of the fiber will be mounted to a translation platform. By indexing the platform to different stations along the tube, a series of circumferential welds will be made by turning the tube for one revolution. Alternately, the

FIGURE 9.

LASER WELDING EXPERIMENT



LASER POWER SUPPLIES
12.25"
EXPERIMENT CONTROLLER
DIODE PUMPED LASER ARRAY
TRANSLATION MOTOR
ROTATION MOTOR
32"
SAMPLE MOUNT
FIBER OPTICS
25"

fiber optic can traverse along a flat specimen and generate a weld bead. Figure 10 illustrates a sample mount which can accomodate flat plates. The change-out of sample mounts will be easily performed by a crew member, making the scheduling of experiments quite flexible.

Due to power limits for an experiment on the Shuttle, this approach will safely operate within the power envelope. Such an experiment would best be manifested to operate in the Shuttle bay as a Hitchhiker-g package, as shown in Figure 11. The current design considerations will meet power, weight and dimensional constraints. The total laser welding package will weigh less than 500 pounds.

By diode pumping, high power arc lamps and complex cooling systems are bypassed. Reliability from simplicity and redundancy are added benefits. The technology is rapidly advancing in this area and in a year, efficiencies and powers will be even higher than the currently available systems claim. Diode pumped lasers presently have the highest efficiencies among the solid state lasers. The designed configuration shown employs commercial lasers which are available from several manufacturers.

Several major factors form the basis for the proposed design. They are:

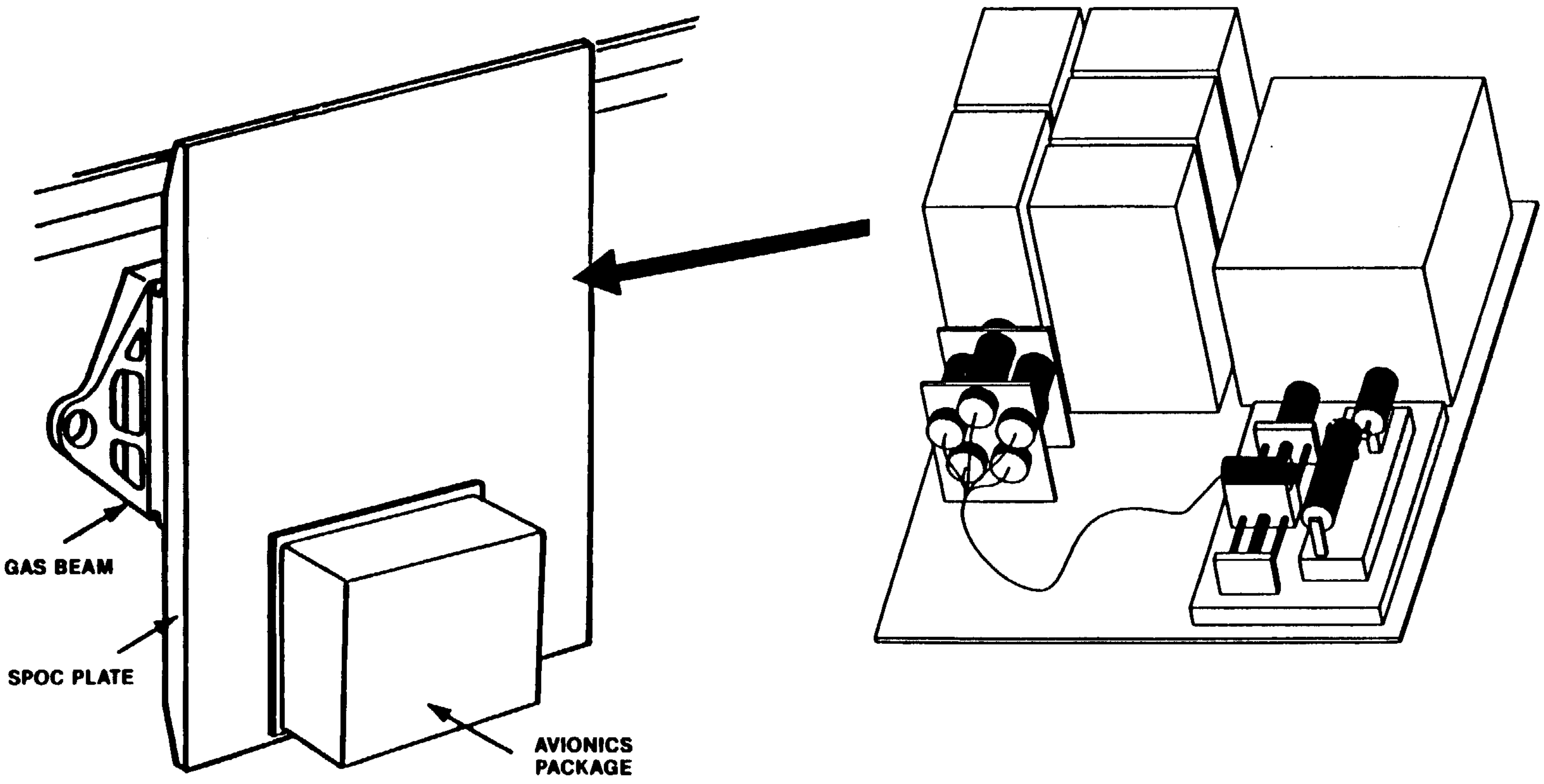
1) Nd-YAG lasers produce the 1 micrometer wavelength most worthwhile for melting metals.

2) diode pumping gives high efficiency with low power consumption.

3) diode pumping reduces cooling problems to an acceptible minimum.

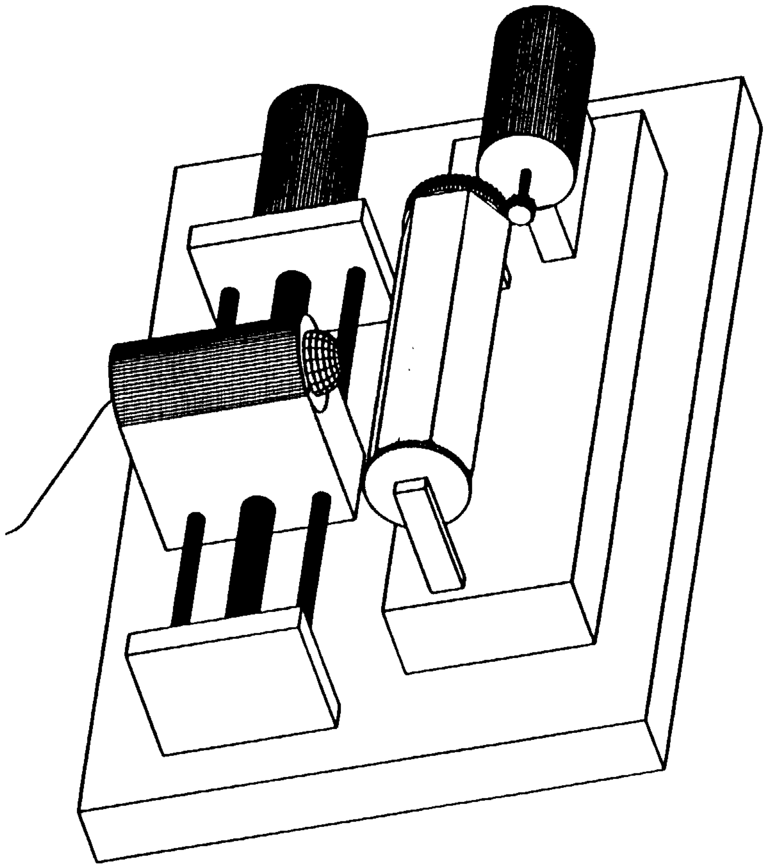
FIGURE 10.

LASER WELDING EXPERIMENT MOUNTED ON HITCHHIKER-g PLATE


GAS BEAM
SPOC PLATE
AVIONICS PACKAGE

The total experiment package for the initial laser welding experiment will occupy one Hitchhiker-g plate and operate in an automated mode of operation.

FIGURE 11.
LASER WELDING EXPERIMENT WITH
FLAT PLATE SAMPLES



This sample holder is interchangeable with the tube holder shown in Figure 9. The samples can be flat plates for a single laser beam translation across the sample or two flat plates to be butt welded length-wise. Multiple samples are welded by rotating the sample mount to obtain access to the next material.

4) fiber optic delivery simplifies the welding process.

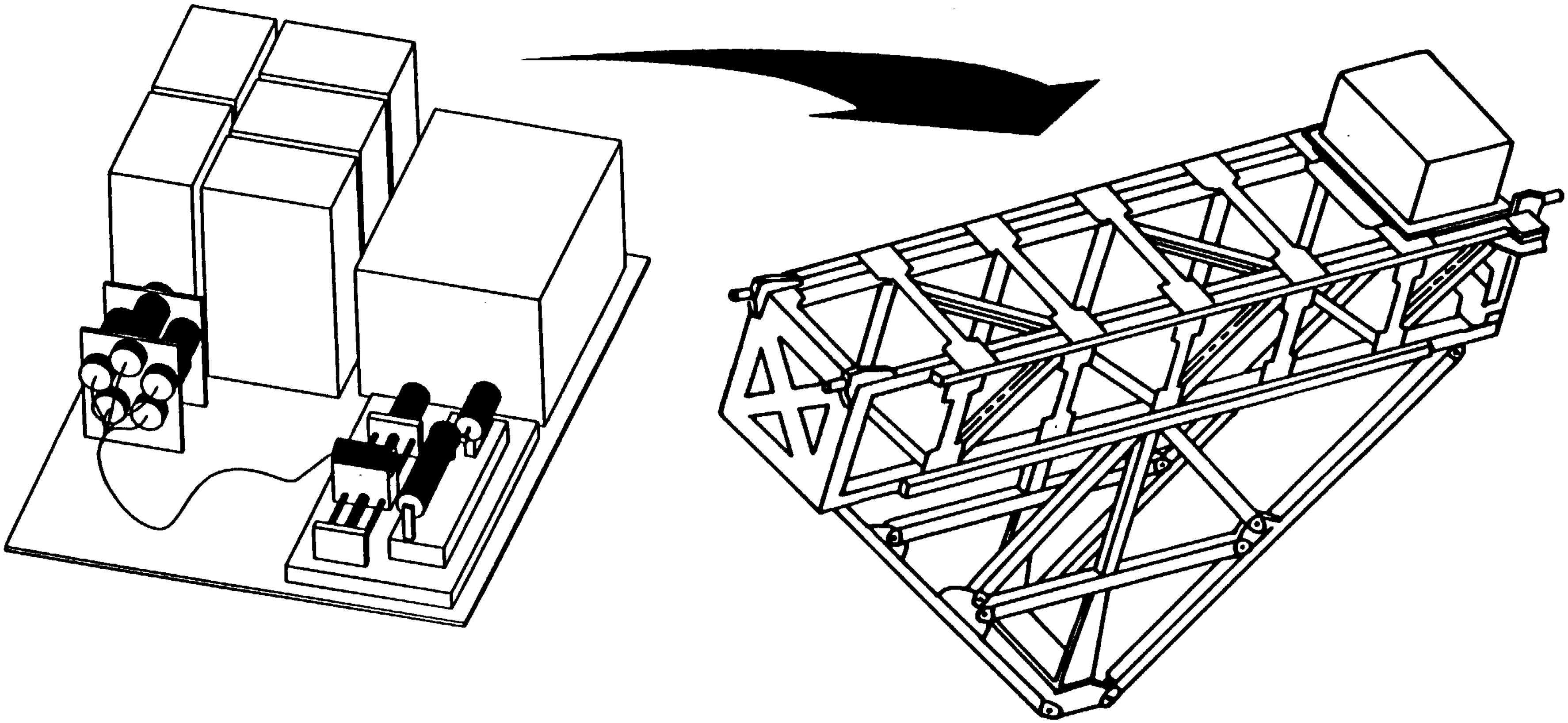
5) bundled fiber optics and multiple lasers make up the design features of the Phase II experiment.

6) Current NASA programs are already working on flight qualifying laser systems of the type required for this experiment.

In addition to the first Shuttle configuration, which will be designed to occupy a Hitchhiker-g pad and operate in an automated mode, we anticipate that a follow-on design for the Hitchhiker-M pallet will also occur. Adding more involvement of the flight crew in manipulating the laser optics to repair welds can be most conveniently configured in that configuration. Figure 12 shows a view of the laser welding apparatus on a Hitchhiker M pallet. The samples can then be placed in a convenient manner for a person to oversee or perform the required welds on top of the bridge structure.

# FIGURE 12.

## LASER WELDING EXPERIMENT MOUNTED ON HITCHHIKER-M BRIDGE



The total experiment package for laser welding experiments will fit onto the Hitchhiker-M bridge and be operable in either an automated mode of operation or manually.

## 7. SUPPORTING ANALYSES

### 7.1 KC-135 EXPERIMENTS

In these experiments, a Nd-YAG laser is used to make an autonomous weld bead in a low gravity environment with the weldment held in a small vacuum chamber. In this way the two properties of space that would influence the quality of a weld are simulated. The whole assembly of the laser, cooling system, data acquisition equipment and human operators were flown on NASA' s KC-135 as it flew parabolic maneuvers to create low gravity. Specimens of 301 or, most often, 304 stainless steel sheet were processed with up to 18 W output multimode of CW 1.06 micrometer laser light. Welding speeds of approximately $1.5 \times 10^{-2}$ m/min were used.

What is so elegant about the analysis is that the variations that are seen are directly attributable to the changes in g-level. The degree of sensitivity when making the comparisons could never be achieved by performing separate runs on separate specimens in subtly different conditions. In our experiments, the only variable that changes in the few seconds of g-transition is the g-level itself. Laser power, focus, specimen absorptivity and emissivity, temperature, vacuum, etc. are all constant for those seconds when the g-level is abruptly reduced or increased.

By using light energy for melting, one needs only to consider heat transfer conditions and their effects on microstructure of the weld. Although power coupling is more efficient With electric current based methods, they introduce strong masking effects (magneto-hydrodynamic convective flows) that prevent clearly observing the effects that a space environment may have on the welding process. Detrimental magnetic and electrical fields are generated by electrical weld methods.

Table 2 shows the flight specimen summary for the project. On five separate occasions welds were made on the KC-135. On two previous occasions, the welding apparatus was taken to Houston for inspection and approval of the hardware to fly. There are 46 specimens listed in the Table. Variations in thickness, material, power level, translation rate and vacuum were made to maximize the quality of the results.

The laser welding apparatus constructed for the KC-135 work used equipment that was readily available during this first phase. For instance the Nd-YAG laser was a GFE laser on loan from Marshall Space Flight Center and the power supply that we used was compatible with the KC-135, but did not easily support Q-switched mode of operation. In these earlier experiments we feel that the data obtained by using a continuous wave output, was useful in that variations in heat transfer caused by going into a low-G environment are not masked by the non-linear effects of laser pulsing. In addition, modeling the thermal behavior is also simplified without pulsing. The additional variables of pulse width, repetition rate and higher absorptivities did not serve to answer the initial questions at hand, so the simplest and most available approach was used. As we go forward in the program, it

# TABLE II
# KC-135 EXPERIMENTS PERFORMED DURING THIS WORK

| SAMPLE ID | MATERIAL & THICKNESS thousandths | LASER POWER WATTS | TRANS RATE cm/min | COMMENTS | POT SETTING | META -LOG | FOCUS | AMPS |
|---|---|---|---|---|---|---|---|---|
| **November 8 - 10, 1988** | | | | | | | | |
| w1188s1 | ss304-36 | 6 | 1.43 | 1 atm. air,no penetration | 2.5 | | 0.1 | 32 |
| w1188s2 | ss301-16 | 6 | 1.43 | 1 atm. air,no penetration | 2.5 | | 0.2 | 32 |
| w1109s1 | ss304-36 | 10 | 1.43 | 1 atmosphere air | 2.5 | | 0.1 | 35 |
| w1109s2 | ss301-16 | 10 | 1.43 | 1 atm. air, window dep. | 2.5 | | 0.1 | 35 |
| w1110s1 | ss304-36 | 8.5 | 1.43 | 1 atm. air, window dep. | 2.5 | | 0.1 | 35 |
| w1110s2 | ss301-16 | 8.5 | 1.43 | 1 atm. air, window dep. | 2.5 | | 0.1 | 34 |
| **December 15 - 16, 1988** | | | | | | | | |
| w1215s1 | ss304-16 | 15.5 | 1.61 | 1 atm. air, no video | 2.7 | | 0.1 | 40 |
| w1215s2 | ss304-8 | 10 | 1.61 | 1 atm. air | 2.7 | | 0.1 | 35 |
| w1215s3 | ss304-8 | 12 | 1.61 | 1 atm. air | 2.7 | | 0.1 | 35 |
| w1216s1 | ss304-8 | 12 | 1.87 | 1 atm. air | 2.7 | | 0.1 | 37 |
| w1216s2 | ss304-8 | 12 | 1.87 | 1 atm. air | 3.0 | | 0.1 | 37 |
| w1216s3 | ss304-8 | 12 | 1.61 | 1 atm. air | 2.7 | | 0.1 | 37 |
| w1216s4 | ss304-8 | 12 | 1.61 | 1 atm. air, level flight | 2.7 | | 0.1 | 27 |
| **March 7 - 10, 1989** | | | | | | | | |
| t37s1 | ss304-5 | 15.5 | 1.61 | vacuum on pre-flight | 2.7 | | 0.2 | 40 |
| t37s2 | ss304-5 | 15.5 | 1.61 | ?amps | 2.7 | | 0.2 | 40 |
| t37s3 | ss304-5 | 15.5 | 1.61 | ?amps | 2.7 | | 0.2 | 40 |
| t389s1 | ss304-5 | 15.5 | 1.61 | vacuum capability | 2.7 | | 0.2 | 40 |
| t389s2 | ss304-5 | 10 | 1.61 | | 2.7 | | 0.2 | 40 |
| t389s3 | ss304-5 | 10 | 1.61 | | 2.7 | | 0.2 | 35 |
| t39s1 | ss304-5 | 12 | 1.61 | | 2.7 | | 0.2 | 35 |
| t39s2 | ss304-5 | 12 | 1.61 | burned through | 2.7 | | 0.2 | 37 |
| t39s3 | ss304-5 | 12 | 1.87 | | 2.7 | | 0.2 | 37 |
| t310s1 | ss304-5 | 12 | 1.61 | | 2.7 | | 0.2 | 37 |
| t310s2 | ss304-5 | 12 | 1.61 | reversed transl. direction | 2.7 | Y | 0.2 | 37 |
| t310s3 | ss304-5 | 12 | 1.61 | varied transl. from 2.7 to 2 | 2.7 | | 0.2 | 37 |

## TABLE II (continued)

| SAMPLE ID | MATERIAL & THICKNESS thousandths | LASER POWER WATTS | TRANS RATE cm/min | COMMENTS | POT SETTING | META -LOG | FOCUS | AMPS |
|---|---|---|---|---|---|---|---|---|
| **April 4-7, 1989** | | | | | | | | |
| t44s2 | ss304-5 | 12 | 1.61 | short weld, quarter inch | 2.7 | | 0.2 | 37 |
| t44s3 | ss304-5 | 12 | 1.61 | | 2.7 | Y | 0.2 | 37 |
| t44s4 | ss304-5 | 12 | 1.61 | short weld, bright im | 2.7 | | 0.2 | 37 |
| t455s1 | ss304-5 | 12 | 1.61 | short weld, quarter inch | 2.7 | | 0.2 | 37 |
| t45s2 | ss304-5 | 12 | 1.61 | short weld, quarter inch | 2.7 | | 0.2 | 37 |
| t45s3 | ss304-5 | 12 | 1.61 | | 2.7 | | 0.2 | 37 |
| t46s1 | ss304-5 | 12 | 1.61 | | 2.7 | | 0.2 | 37 |
| t46s2 | ss304-5 | 12 | 1.61 | | 2.7 | | 0.2 | 37 |
| t46s3 | ss304-5 | 12 | 1.61 | vacuum pump flown | 2.7 | Y | 0.2 | 37 |
| t46s4 | ss304-5 | 12 | 1.61 | pump cavitated during 0-G | 2.7 | | 0.2 | 37 |
| t47s1 | ss304-5 | 12 | 1.61 | good vacuum, poor penet. | 2.7 | | 0.2 | 37 |
| t47s2 | ss304-5 | 12 | 1.61 | reversed transl. direction | 2.7 | Y | 0.2 | 37 |
| t47s3 | ss304-5 | 12 | 1.61 | | 2.7 | Y | 0.2 | 37 |
| t47s4 | ss304-5 | 12 | 1.61 | | 2.7 | Y | 0.2 | 37 |
| **June 6-9, 1989** | | | | | | | | |
| s60889s1 | solder-27 | 10 | 1.61 | air | 2.7 | | 0.2 | 35 |
| s60889s2 | solder-27 | 10 | 1.61 | didn't melt | 2.7 | | 0.2 | 35 |
| w60889s3 | ss304-5 | 15.5 | 1.61 | 300mT, not clamped | 2.7 | | 0.2 | 35 |
| s60989S1 | solder-27 | 10 | 1.61 | air | 2.7 | | 0.2 | 40 |
| w60989S2 | SS304-5 | 15.5 | 1.61 | vacuum, 500 mT, no data | 2.7 | | 0.2 | 35 |
| w60989S3 | SS304-5 | 15.5 | 1.61 | vacuum, 300 mT | 2.7 | | 0.2 | 40 |

has become obvious that pulsed laser welding may be more appropriate for Space applications.

## 7.2 KC-135 APPARATUS DESIGN REQUIREMENTS

Preparing the apparatus to fly on the aircraft and adapting the various components for microgravity conditions became the dominant effort. A major advantage in using a Nd-YAG laser, besides its availability for our experiments, is its smaller size in comparison to a $CO_2$ gas laser. Experiments to be flown on the KC-135 are restricted to size and weight limits, although other researchers have flown smaller power $CO_2$ lasers on the KC-135. As shown previously in Figure 4, the Nd-YAG laser also produces a shorter wavelength emission which couples more efficiently with the weld alloys used.

All apparatus that was flown on the KC-135 had to be ruggedly constructed for safety reasons. The YAG laser is inherently rugged. The laser used, considering its age, was as high in power consumption as possible for the KC-135 environment. Our laser was a 15 year old model 114 dual lamp Quantronix Nd-YAG designed for 38 watts output continuous in multimode. Power measurements revealed that the beam power was no greater than 18 W prior to entering the beam delivery system. Beam characteristics are 2mm diameter, 6 mr divergence and 5% rms stability. Power for the laser arc lamps had to be supplied from the aircraft power bus (which feeds 400Hz 208V three phase power). To operate the laser head from the aircraft power, a special power supply, the 10KW YAG-Drive from ALE Inc. was used.

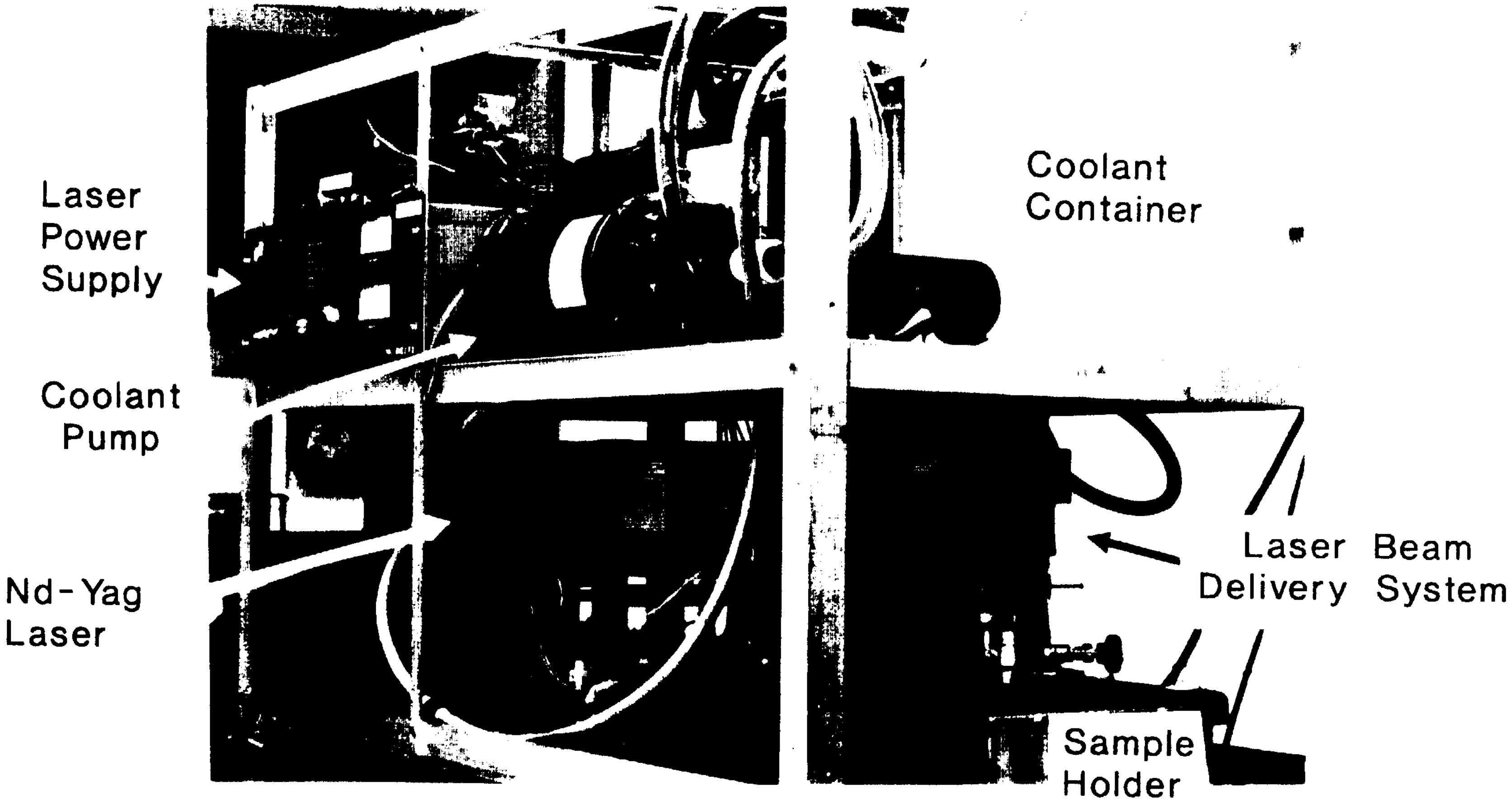
This power supply could operate from the 400Hz frequency and is more compact than most other supplies of equal or less power capacity. Power inverters in the aircraft do supply 120V 60Hz power for the other instruments.

The standard cooling system (containing filters, deionizers, and heat exchangers) was not used with the laser system. Instead, a truly bare-bones coolant supply was fabricated. All cooling is supplied by 20 liters of de-ionized water circulated through the laser head by a 1/3 HP 120V AC impeller pump. This pump can provide the 6 gal/min and 20 psi pressure that prevents lamp and crystal damage. The cooling system limitation, in conjunction with logistics of changing samples during parabolic maneuvers, permitted up to 4 specimens to be processed per flight. Note that the cooling system has to function properly in a microgravity environment and operate with considerable reliability for aircraft personnel safety. Cooling water temperature was kept below 40 °C to protect the laser head.

An aluminum frame of 60x70x120 cm houses the laser, beam delivery system, power supply and cooling system. This is shown in Figure 13. The experiment is performed inside this apparatus with aluminum sheet fully covering the exterior of the frame for safety reasons. There is no control over the experiment except translation speed and power to the laser once the box is closed. There have been no alignment problems either with the laser resonator cavity or the beam delivery system. This is not a trivial statement given that the equipment is trucked thousands of miles to and from the airfield between flights. Several

ORIGINAL PAGE
COLOR PHOTOGRAPH

FIGURE 13.
BREAKOUT OF THE LASER WELDER
FLOWN ON THE KC-135


Laser Power Supply
Coolant Pump
Nd-Yag Laser
Coolant Container
Laser Beam Delivery System
Sample Holder

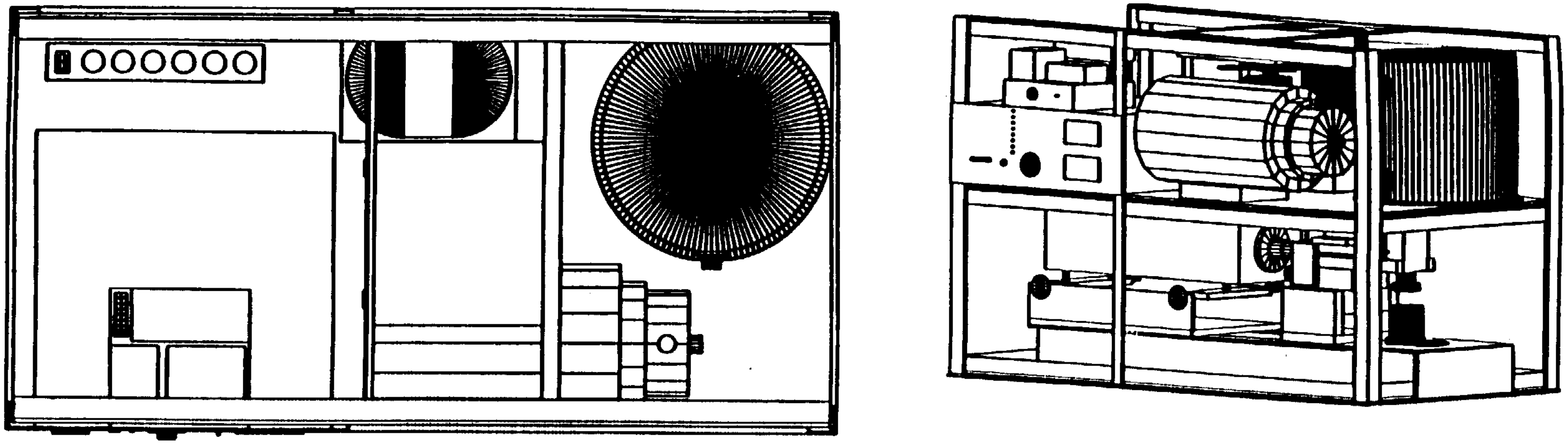
perspective views of the experiment package also provided in Figure 14.

A heavy and precise translator system is used for the beam delivery/translator. Without precision optical grade screw drives, the raising and lowering of the gravity level during the experiment could alter the laser focus. The translator supports the beam delivery optics and the video imaging system. A closed circuit television system is used for the observation of the welding process. The numerical data is recorded with an 80286 based computer. The interconnections for the system as a whole are shown in Figure 15.

By employing a video overlay circuit, the computer graphics and data are superimposed on the magnified weld pool image as it is being recorded on the S-VHS VCR. A S-VHS monitor provides the experimenters an instantaneous view of all conditions during the run. By using a hot-mirror and filters, the camera can view the weld pool along the same optical axis as the laser beam. Figure 16 is a schematic of the optical path. The exit beam from the laser passes through a 4X beam expander and then a dichroic hot-mirror tuned to the YAG wavelength reflects the beam down through the focusing lens onto the weldment after passing through the window of the vacuum chamber. The focal length of the lens is 1.5 inches. The weld pool is imaged by the beam-focusing lens up to the camera. The camera used is a CCD type (NEC TI-23A). A visible pass interference filter is placed in the camera optical path to see the weld pool. Early tests showed strong laser reflection from the molten metal pools. The combination of

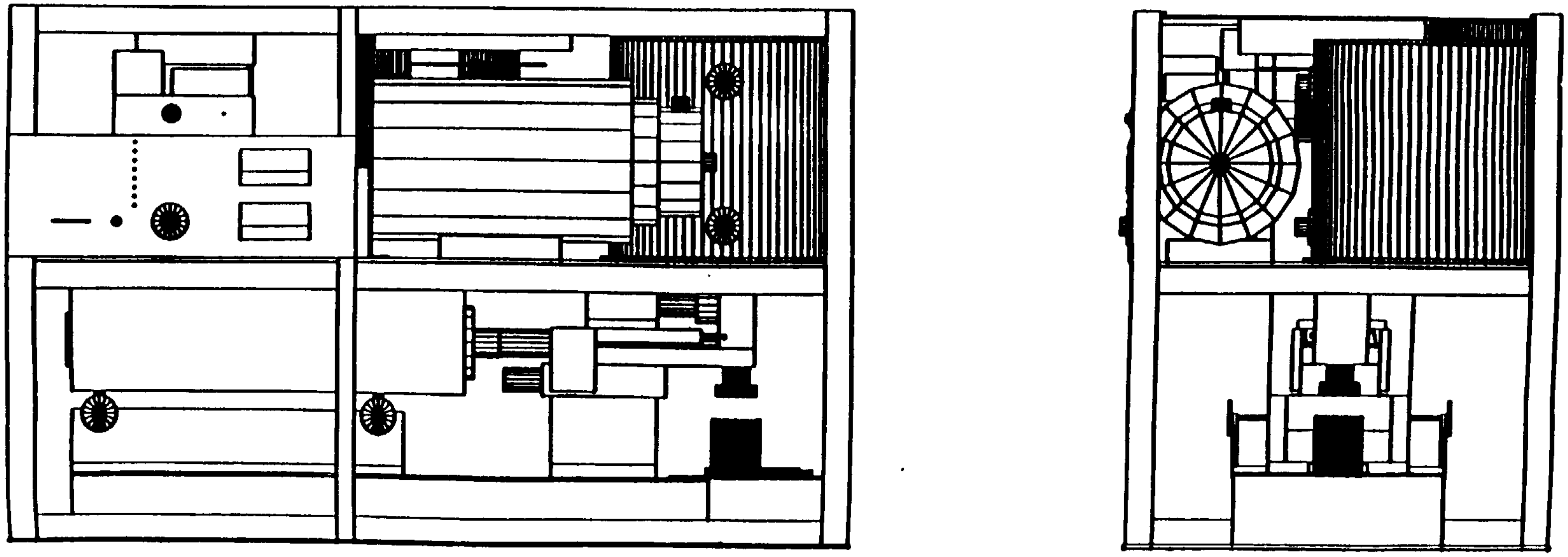
# FIGURE 14.

VARIOUS VIEWS OF THE
KC-135 LASER WELDING EXPERIMENT



a.) Top View

b.) Right Front View

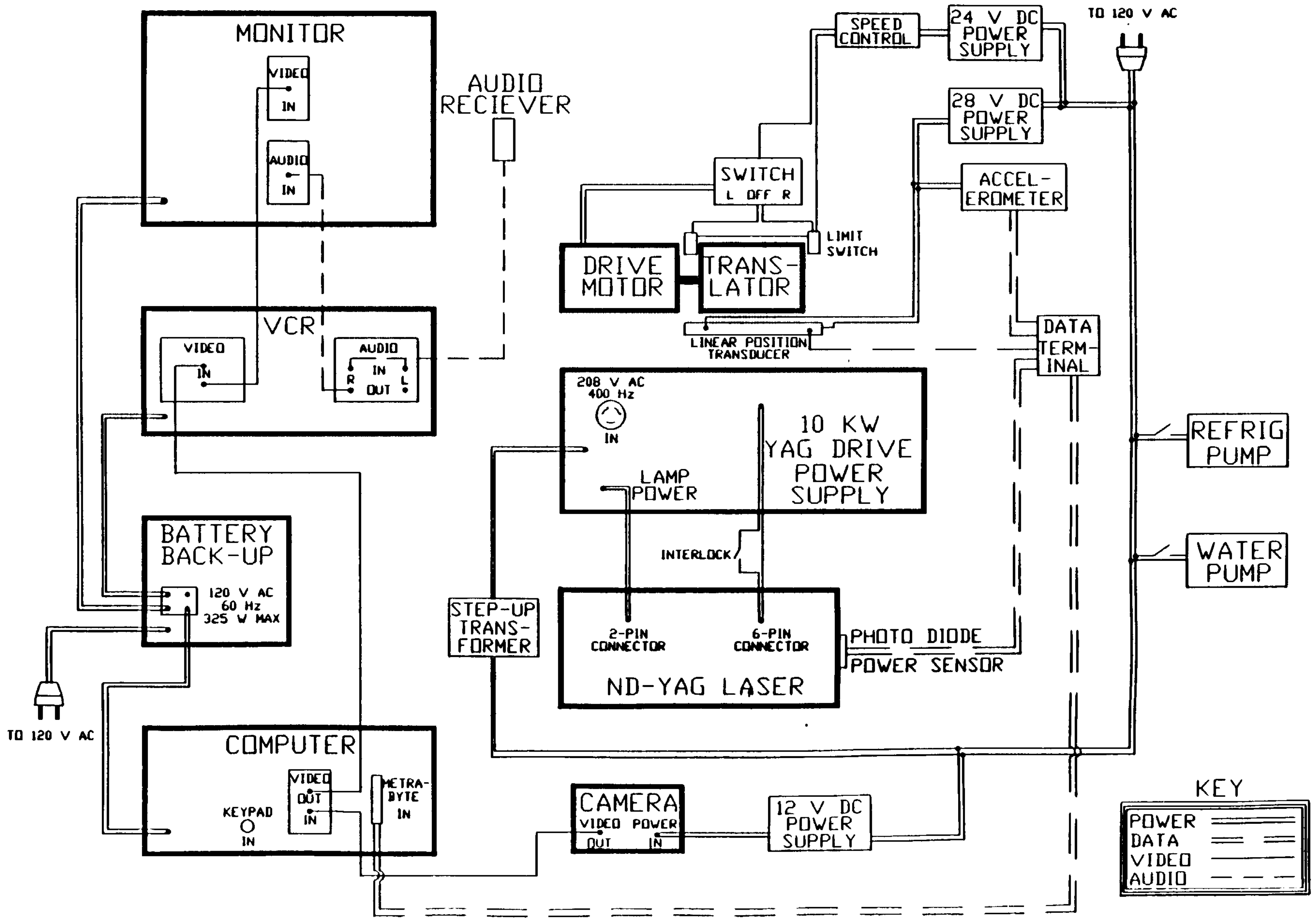


c.) Front View

d.) Side View

FIGURE 15.

EXPERIMENT INTERCONNECTIONS FOR THE KC-135 LASER WELDING EXPERIMENT

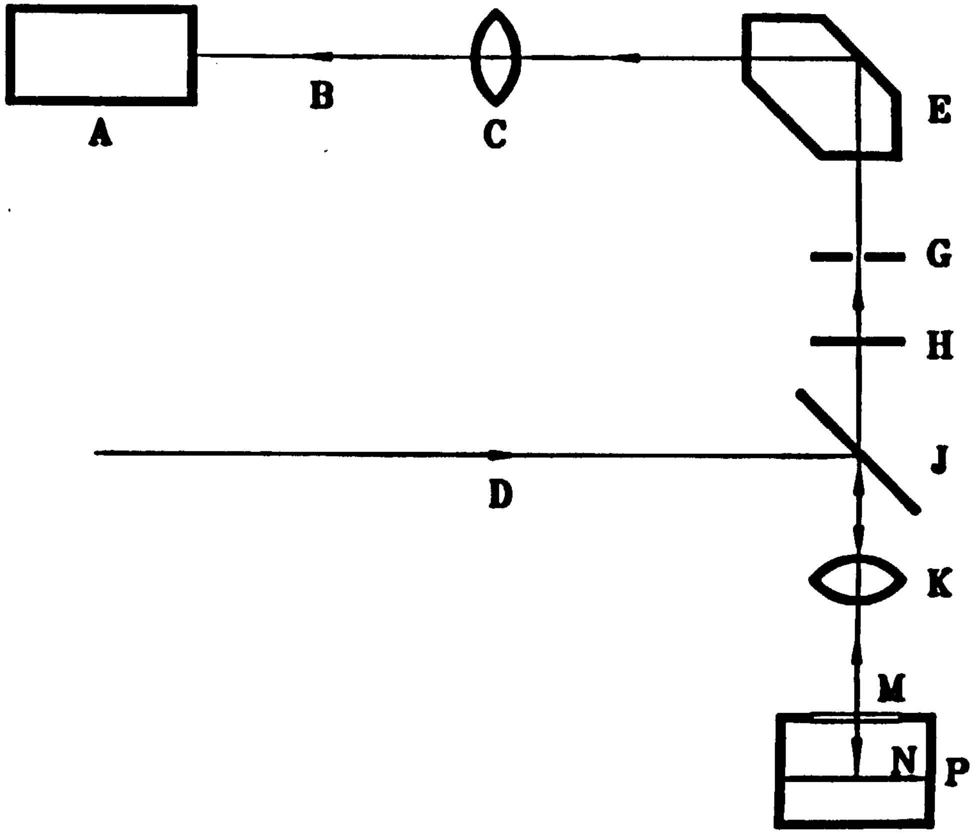

MONITOR
VIDEO IN
AUDIO IN
AUDIO RECIEVER
VCR
VIDEO IN
AUDIO IN R L OUT
BATTERY BACK-UP
120 V AC 60 Hz 325 W MAX
TO 120 V AC
COMPUTER
VIDEO OUT IN
KEYPAD IN
METRA-BYTE IN
STEP-UP TRANS-FORMER
SPEED CONTROL
24 V DC POWER SUPPLY
28 V DC POWER SUPPLY
TO 120 V AC
SWITCH L OFF R
LIMIT SWITCH
ACCEL-EROMETER
DRIVE MOTOR
TRANS-LATOR
LINEAR POSITION TRANSDUCER
DATA TERM-INAL
208 V AC 400 Hz IN
10 KW YAG DRIVE POWER SUPPLY
LAMP POWER
INTERLOCK
2-PIN CONNECTOR
6-PIN CONNECTOR
ND-YAG LASER
PHOTO DIODE
POWER SENSOR
REFRIG PUMP
WATER PUMP
CAMERA
VIDEO OUT
POWER IN
12 V DC POWER SUPPLY
KEY
POWER
DATA
VIDEO
AUDIO

# FIGURE 16.

## TV CAMERA OPTICS FOR THE KC-135 LASER WELDING EXPERIMENT

**Beam Delivery**
**and Video Optics**

**A. CCD Camera**
**B. Image to Camera**
**C. TV Focus Lens**
**D. Expanded Laser Beam**
**1.06u, 18W maximum**
**E. Prism**
**G. 3/16" Aperature**
**H. Interference Filter**
**J. Band Pass Mirror**
**K. Laser Focus Lens**
**M. Chamber Window**
**N. Sample**
**P. Vacuum Chamber**



lenses used gives a net 80 magnification to the monitor screen. The weld pool image is about 0.8 cm in diameter on the screen. To see moving features clearly, the camera operates at a shutter speed of 1/1000 second per frame.

The sample container used to simulate low gravity and space for the KC-135 experiments is shown in Figure 17. The vacuum valve and thermocouple gauge provided access for evacuating the chamber to a specified pressure. Figure 18 shows a further breakdown of the components used to fabricate the specimens for flight. Although the intent was to provide a specific pressure in the chamber for each sample, the O-rings shown in the figure never did function properly. Hence the 'space' simulation was not very accurate. A vaccum pump was included in the flight hardware on later flights; however, even then the leakage around the seals allowed the pressure to rise continuously. The roughing pump used for the experiments contained oil and could not run in low G. An oil-less pump was too expensive for this phase of the work and was not available for the experiments. This chamber will be redesigned for future KC-135 experiments.

Attached to the translation head was a precision linear potentiometer such that the head position could be monitored. The device served three main purposes:

a) to relay the head position to the operator without having to open the light baffles on the aircraft. This was necessary to bring the translator head to its standard starting position.

b) to monitor the position of the translator head with time during the course of the experiment.

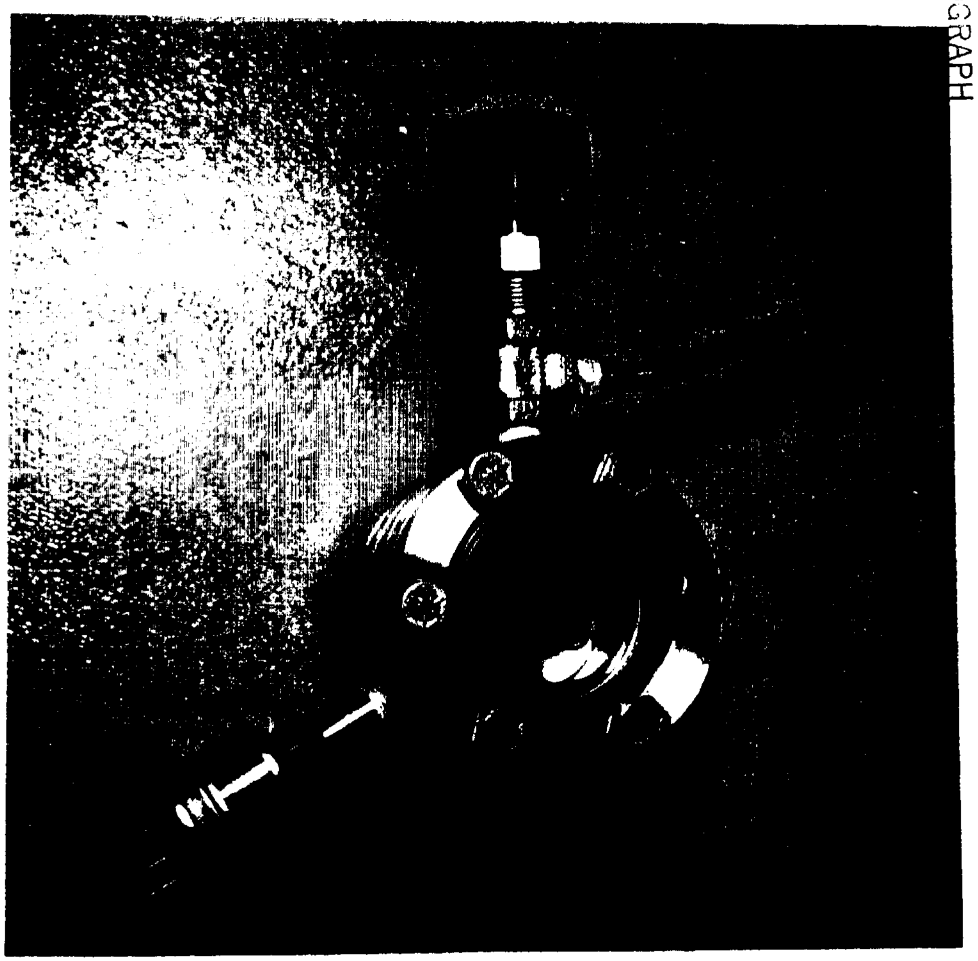
c) to measure the welding rate.

# FIGURE 17.

## SAMPLE CHAMBER FOR LASER WELDING EXPERIMENTS

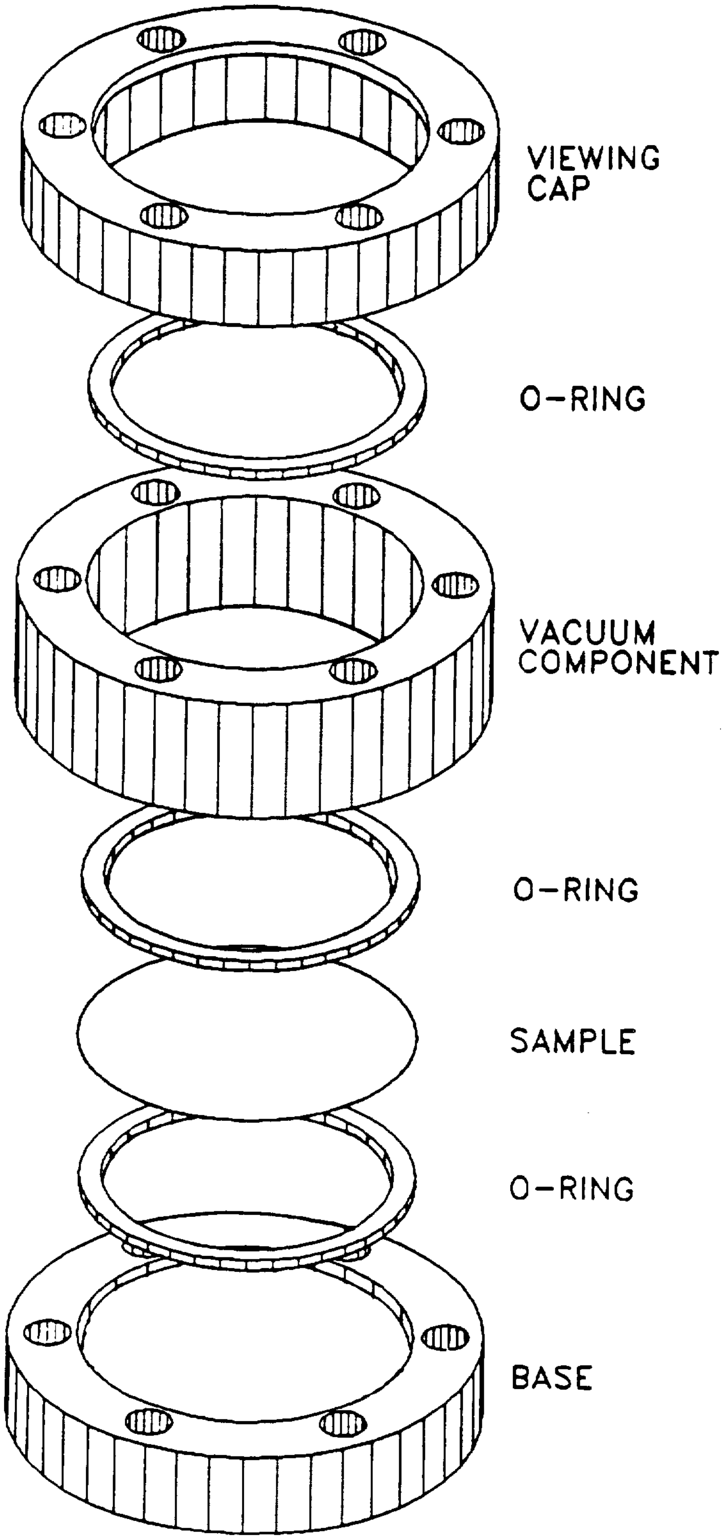
ORIGINAL PAGE
COLOR PHOTOGRAPH

THIS IS A PHOTOGRAPH OF THE SAMPLE CHAMBER CONTAINING A PROCESSED SAMPLE FROM A KC-135 LASER WELDING EXPERIMENT. THE VACUUM VALVE AND THERMOCOUPLE GAUGE ALLOW SIMULATED "SPACE" WELDING DURING LOW G. THE WELD BEAD CAN BE SEEN IN THE PHOTOGRAPH. FIGURE 18, WHICH FOLLOWS, SHOWS THE DIFFERENT COMPONENTS WHICH MAKE UP THE CHAMBER.



## FIGURE 18.

## VACUUM CHAMBER SAMPLE CONFIGURATION FOR KC-135 LASER WELDING EXPERIMENT


VIEWING CAP
O-RING
VACUUM COMPONENT
O-RING
SAMPLE
O-RING
BASE

An accelerometer was also mounted to the translation head in the vertical direction. From this, the major axis acceleration levels could be monitored during the flight and recorded for each specimen.

Translation rate was adjusted manually for these experiments. A potentiometer controlled a voltage through a regulated circuit which powered a DC gearhead motor. The motor turned a precision screw drive in the translator head resulting in linear movement. Safety limit switches were employed to prevent damage of the apparatus since translation was not controlled by computer. A calibration of the translation mechanism is shown in Figure 19.

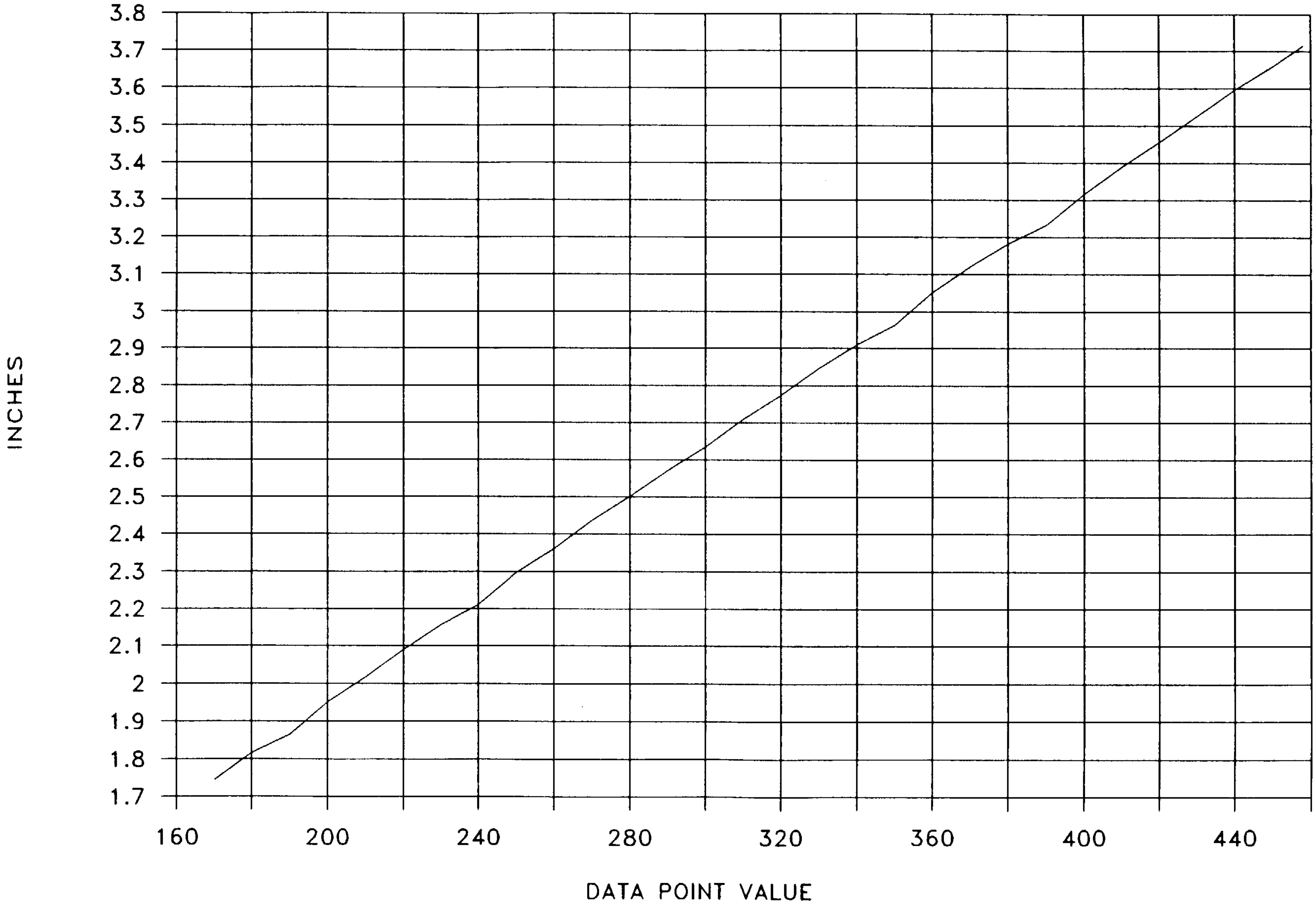
The output power of the laser as measured through the optics of the delivery system and chamber window was measured using a Coherent Model 102 Laser Power Meter. A calibration was established between the diode in the laser to the power at the between the diode in the laser to the power at the specimen. Changes in laser power were affected by the power into the laser which was recorded as amperes in. Power was not a strict function of amperes alone as water temperature and condition of the lamps and optics also had an effect.

## 7.3 SPECIMEN ANALYSIS AND METALLOGRAPHY

As each specimen was received, careful examination of the weldment surfaces was performed. The welds were evaluated

# FIGURE 19.

## LASER WELDING TRANSLATOR CALIBRATION



for suitability to be further tested. Specimens without irregularities or known artifacts that reduced viability for data collection were culled for detailed examination and sectioning. Surface features of each selected weldment were photographed by optical microscopy prior to sectioning. During the experiment, position and acceleration data were collected by the computer and later mapped onto the weld bead by hand.

Cut pieces of weldments were mounted in Bakelite and mechanically polished through to 0.05 micrometer Alumina. Kalling's etchant or electrolytic etching with dilute oxalic or nitric acid was used to reveal structure. Both transverse and longitudinal cross sections were made. Transverse sections reveal the weld pool shape in a plane normal to the translation axis. The longitudinal section cuts the weld bead vertically in the plane containing the translation axis. This latter cut reveals microstructural variations from front to back in the pool. The trailing edge and convective patterns near this edge of the weld pool are clearly visible. variations in partial penetration with position are seen in one cut. A few sections were tested for microhardness using a diamond pyramid indenter.

It should be noted that not all specimens were found to be suitable for metallographic examination. Certain combinations of material thickness, power and translation rate produced inadequate penetration for metallography.

## 7.4 RESULTS

Nearly all the welds made were of high quality. When air was in contact with the weld pool however, cracking, oxide deposits and materials losses were incurred. At small air pressures of 500 mTorr or less, the welds were relatively clean and crack free. The heat affected zones were less wide than the fusion zones. Appreciable grain growth was seen in the HAZ next to the fusion zone.

In November and December, 1988, there were a series of KC-135 experiments run with the laser welding apparatus. Experiments done on the ground confirmed a new observation that the weld characteristics of earlier flight experiments were directly attributable to the presence of oxygen in the weld chamber during the weld procedure. Here are the characteristics observed:

1. The brightness of the weld zone was significantly higher when oxygen was present in the weld chamber, at pressures of 500 mTorr or higher.

2. The variation in weld brightness had a higher deviation from an average when oxygen was present in the chamber.

3. Welds made with vacuum levels of 200 mTorr or better did not produce smoke or fume which could have clouded the window. Nor was there any black or brown deposits in the vicinity of the weld zone.

4. Welds made on the ground under good vacuum conditions did not yield as deep a level of penetration as those made in flight with poor vacuum. Operating the laser at power levels slightly higher than during flight did not improve the penetration.

Measurements were made from the video tapes using image processing techniques which showed two things: one, there was no structural detail within the bright flashes of light that were recorded. Second, when the laser power was shut off at the end of a run, emission of radiation from the hot metal of the weld pool did not have sufficient strength to register on the CCD due to the high degree of attenuation used. It became clear that the small weld pool size prevented visualization of fluid-dynamic events. The narrow band-pass filter prevented the visualization of the thermal gradients.

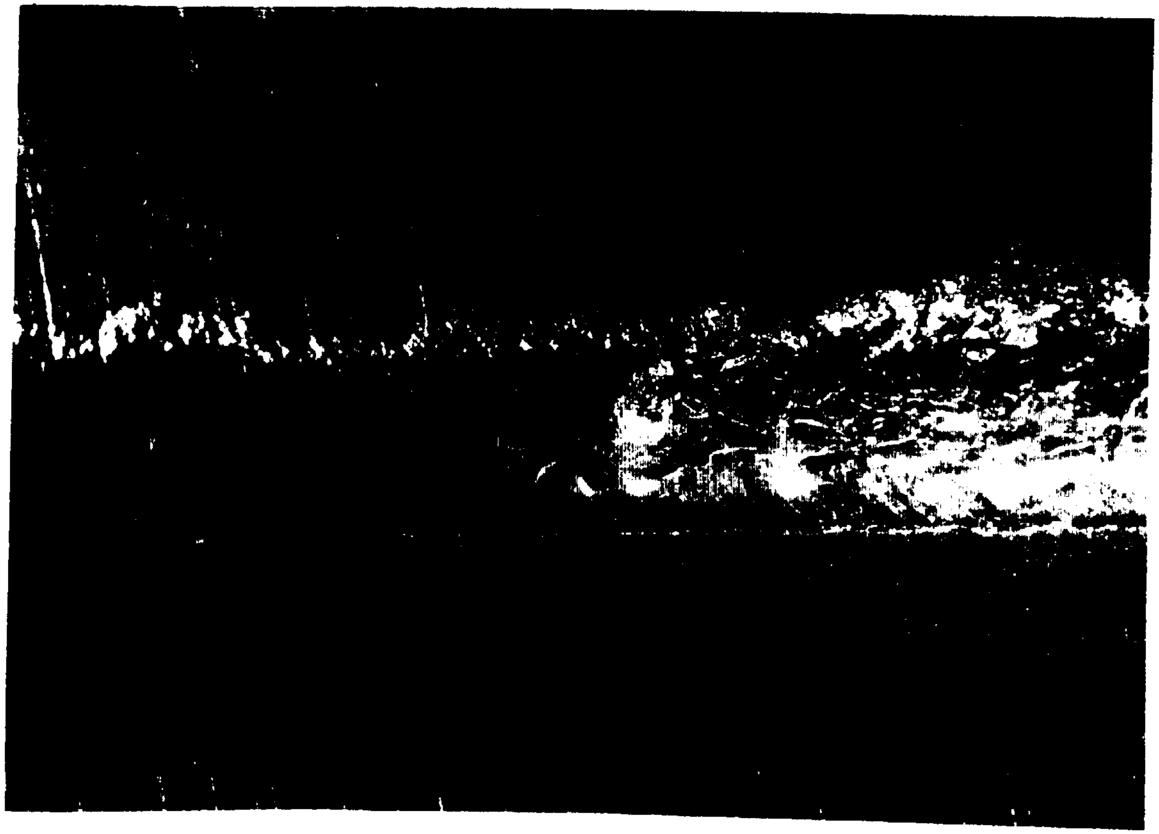
The weld pool shape is a near perfect circle when viewed from above. This can be determined from the weldment by the shape of the ripples formed at the trailing edge of the pool. Such rippling is shown in Figure 20 for 0.127 mm thick 304 stainless steel sheet. In this micrograph, ripples were suppressed in high gravity conditions. Structural weakening of the weld will occur if the ripples become severe. Weld ripples are extensively discussed in Anthony and Cline[1]. Both Zacharias[8] and Lin[5] found as we did that the pool liquid profile or shape affects the convection path and therefore the heat transfer process.

The microstructure of the laser welds generated in the KC-135 experiments provide interesting analyses. Typical examples are specimens t46s2, t47s3, and t39s1 which are shown in Figures 21-23. These micrographs show transverse weld sections of specimens where one is from a 1.8 g portion of the experiment and the other formed in 0.01 g conditions. These are full penetration

ORIGINAL PAGE
COLOR PHOTOGRAPH

## FIGURE 20

## LASER WELDING IN SPACE
## POST WELD SURFACE STRUCTURE

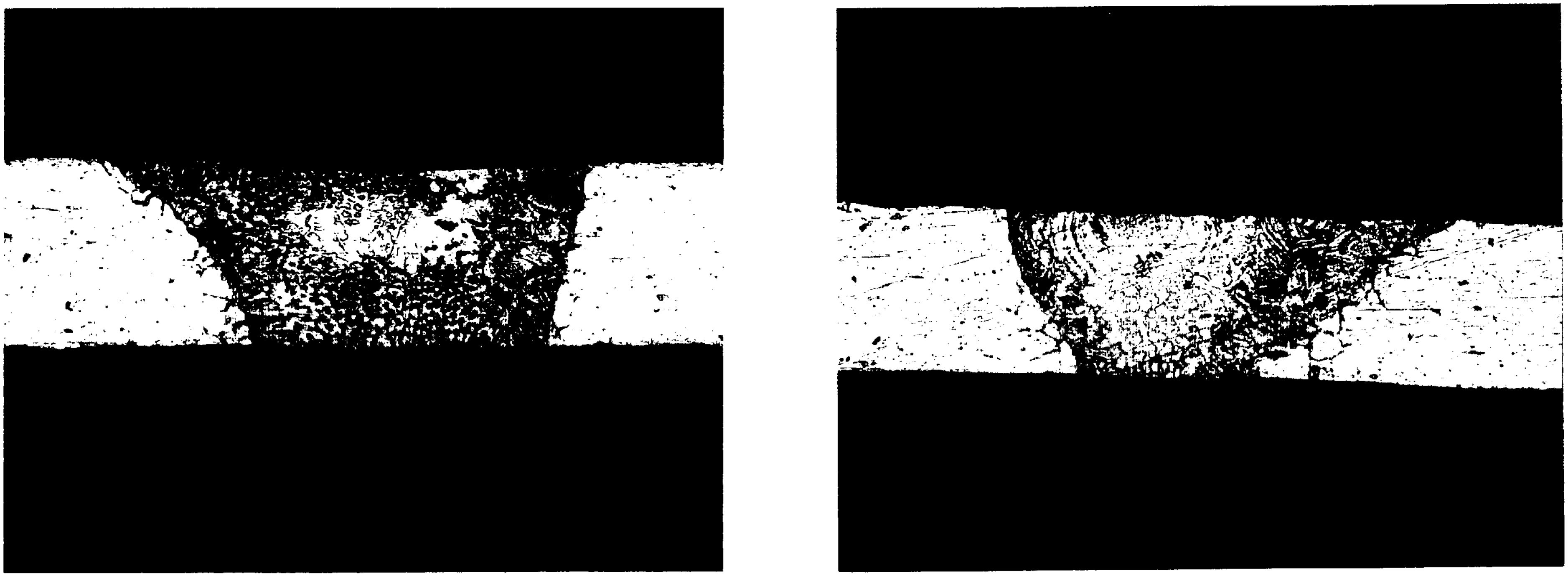


Sample T39S1 is stainless steel 304 (0.127 mm thick). Weld surface at 85X, dark field optical topography, shows ripples in low G portion on right half of photograph. Left half is high G portion and shows little rippling.

# FIGURE 21

# LASER WELDING IN SPACE

## TRANSVERSE MICROSTRUCTURES 304 STAINLESS



HIGH (1.8) G

LOW (0.1) G

OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 200X

SPECIMEN T46S2

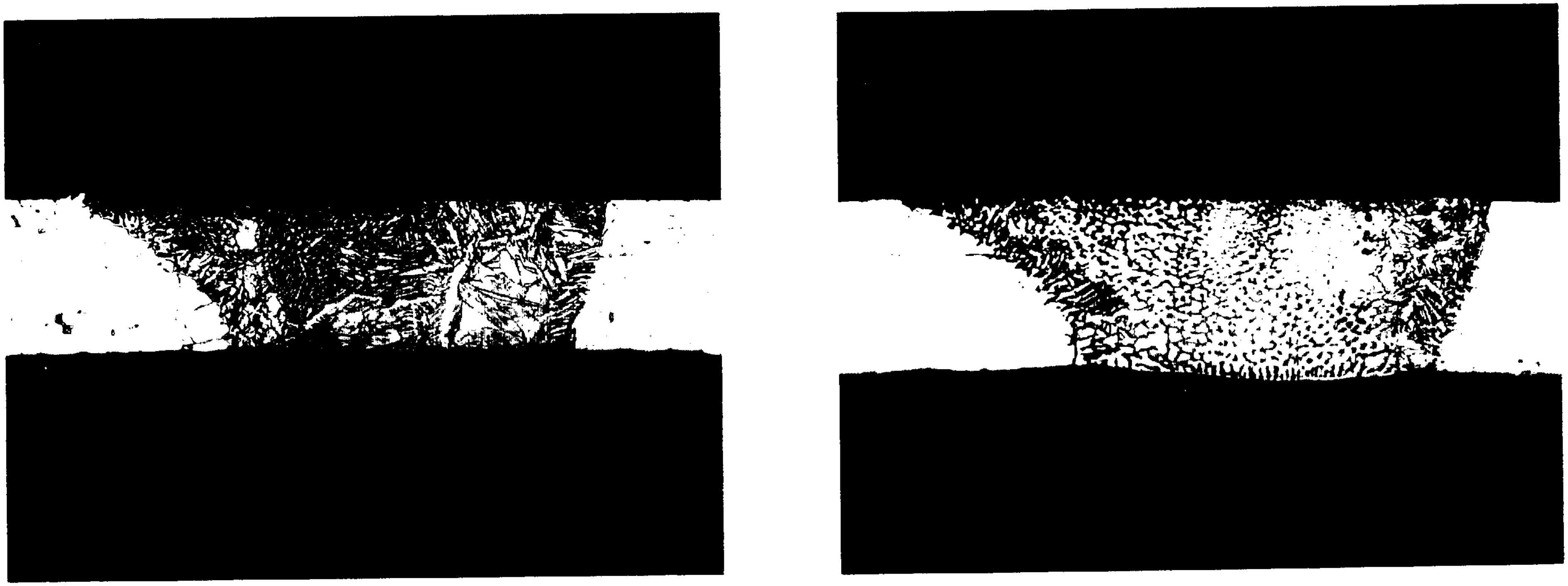
ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

# FIGURE 22

# LASER WELDING IN SPACE

## TRANSVERSE MICROSTRUCTURES 304 STAINLESS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



HIGH (1.8) G

LOW (0.1) G

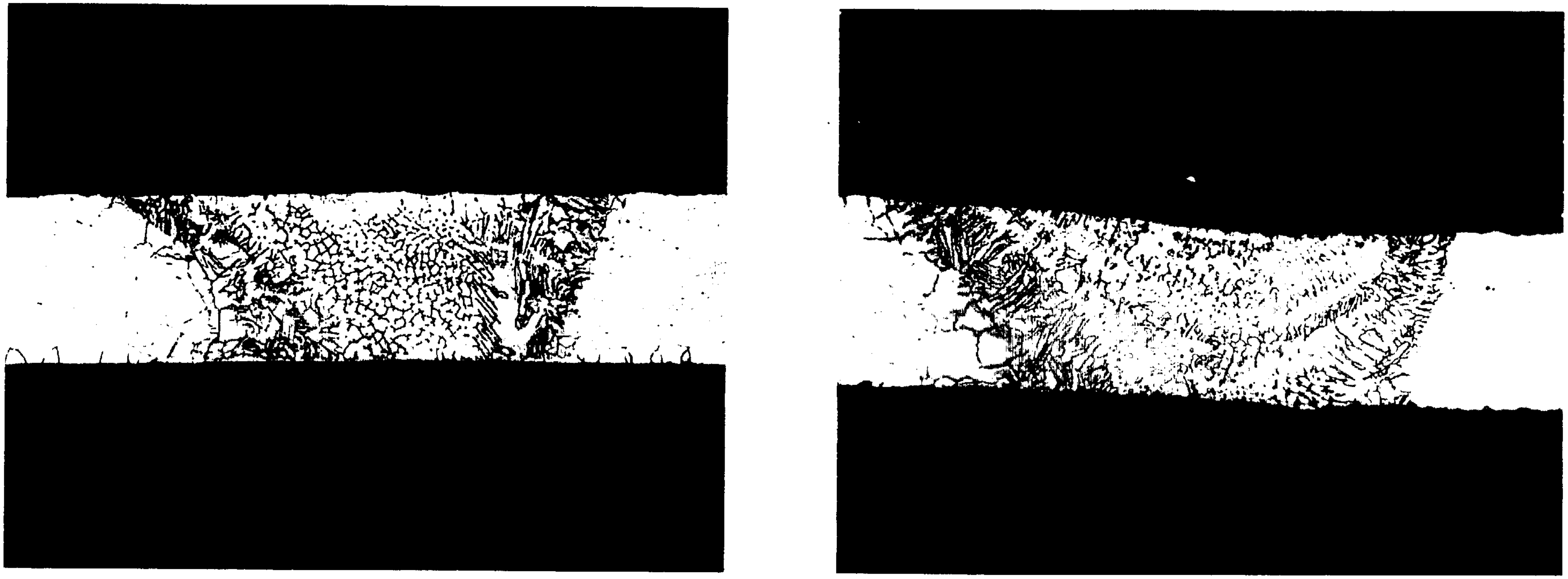
OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 200X

SPECIMEN T47S3

# FIGURE 23

# LASER WELDING IN SPACE

## TRANSVERSE MICROSTRUCTURES 304 STAINLESS



HIGH (1.8) G

LOW (0.1) G

OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 200X

SPECIMEN T39S1

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

autogenous welds. The first figure of the series best represents the type of microstructure observed. The equiaxed dendritic microstructure of the high-g weld resulted from the higher convection velocities possibly due to the buoyancy convection contribution. A radial (to the weld axis) columnar structure can be seen in the low-g weldment. Each of the low-g sections in the series has a radially emphasized microstructure while the high-g sections have a random or mixed orientation to the structure. In low-g the heat flow pattern is radial as is the solidification direction. Such behavior results from a reduction in convective flow. It is our contention that buoyancy driven convection effects are nearly zero in our weld pools and during low-g conditions, it is more likely that the changed shape of the molten pool causes the changes in heat flow.

By removing gravity, a higher curvature can be sustained in the liquid surface of the bead. If surface tension is the main driving force and not significantly reduced by higher temperatures, then the width of the weld pool should diminish. Since heat input is not reduced, the amount of metal that melts should not change. Except for heat transfer arguments, the pool volume stays constant and as a result, if it is a partial penetration weld, the degree of penetration should increase. This argument is not reversed if the temperature coefficient of surface tension is positive. Heiple, et al[7] added sulfur to 304 stainless welds and reversed convection by inverting the temperature coefficient of surface tension. It is the high value of surface tension that causes capillary effects and the bulk expansion of the molten metal that causes the pool to bulge. Thermal gradients in the surface should alter the overall shape but not dominate the shape defined by the expansion and capillarity.

Figure 23 shows the post weld surface structure at the point in its travel when the acceleration level drops from 1.7g to 0.01g. The picture shows 7.3 seconds of weld time. A reduction of weld bead width by 17% (from 383 to 319 micrometers) can clearly be seen. With the full penetration welds of Figures 21 and 22, which have two fluid-gas free surfaces, the bead width seems less affected by acceleration level.

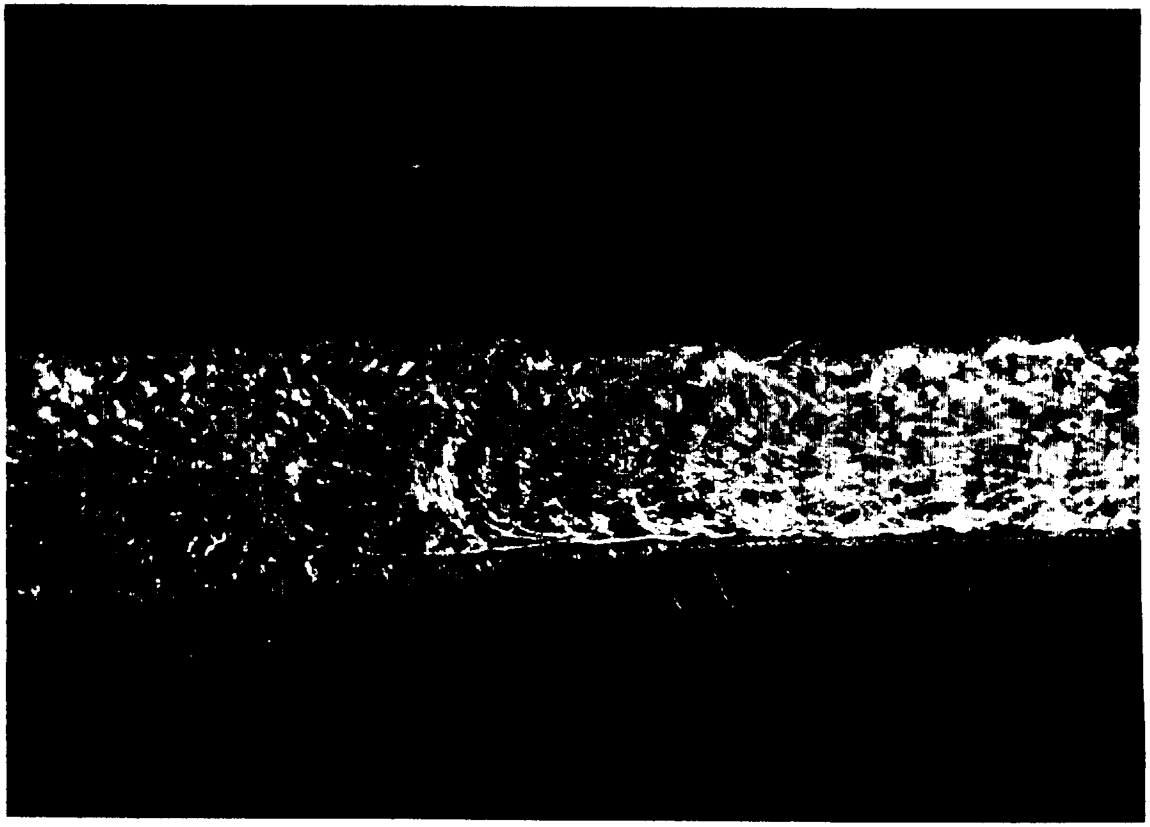
Although extremely difficult to perform, a longitudinal section of a partial penetration weld was made. Figure 24 shows this section made along the weld direction. This micrograph shows the degree of penetration and how it changed as the laser continuously melted metal in high-g and then in low-g. Figure 25 also shows another acceleration shift in the same specimen. In this figure, the transition shown is from high to low gravity. A surprisingly large increase of 50% in the penetration depth occurred under microgravity conditions. The two figures demonstrate that the step up in acceleration level or the step down both produce similar results. This indicates that weld pool volume is maintained as the weld bead width diminished in low-g. From this we see that heat input to the pool is relatively constant. Heat flow and convection strengths must however be different between the two g-levels.

It is important to note that not every specimen manifested

ORIGINAL PAGE
COLOR PHOTOGRAPH

# FIGURE 24

# LASER WELDING IN SPACE POST WELD SURFACE STRUCTURE

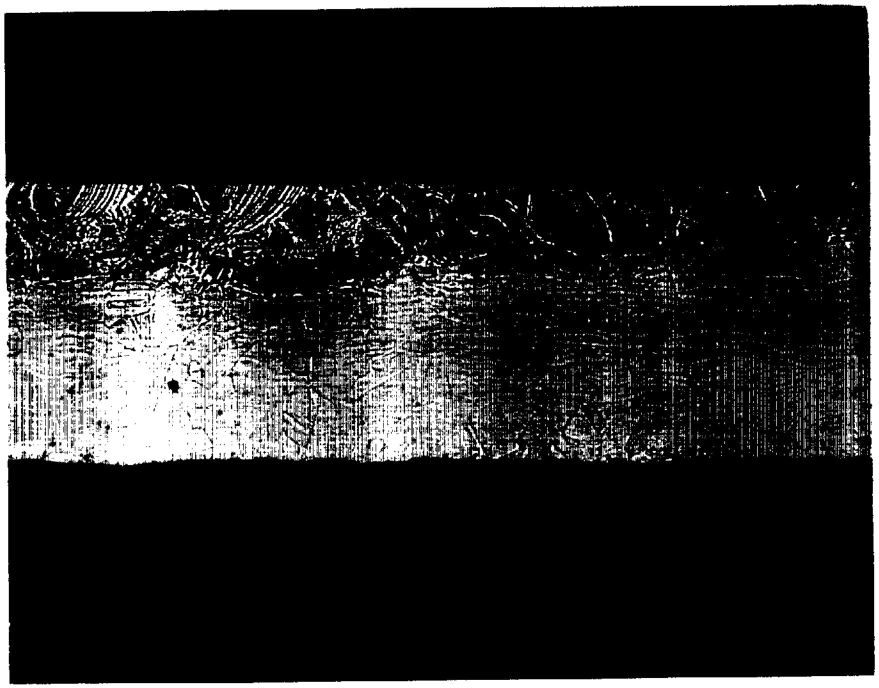


Sample T38S1 is also stainless steel 304 (0.127 mm thick). Micrograph shows 17% reduction in bead width in transit from high to low G. Rippling is also slightly greater in low G.

# FIGURE 25

# LASER WELDING IN SPACE

## TRANSVERSE MICROSTRUCTURES 304 STAINLESS



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

LOW G (0.1) TO HIGH G (1.8)

OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 200X

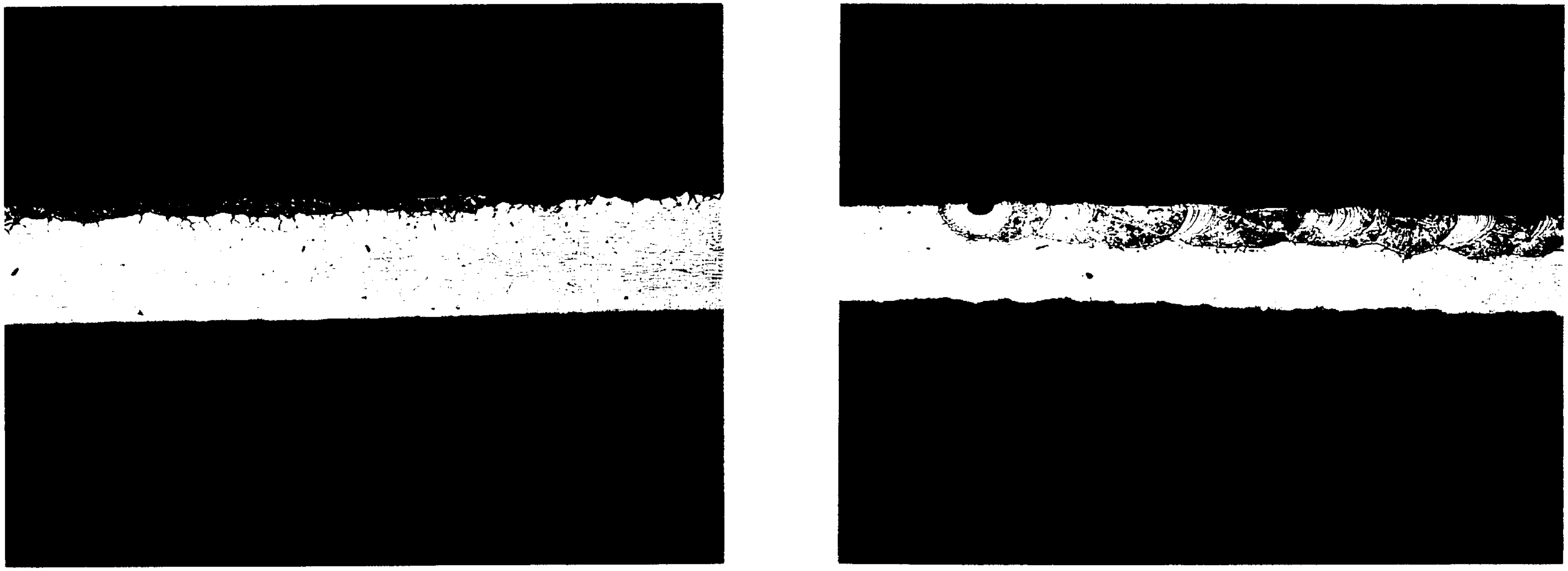
SPECIMEN T310S1

# FIGURE 26

# LASER WELDING IN SPACE

## TRANSVERSE MICROSTRUCTURES 304 STAINLESS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



HIGH (1.8) G

LOW (0.1) G

OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 100X

SPECIMEN T310S1

visible changes in structure in sympathy with g-level changes. Many specimens showed no alteration in bead width as seen on the surface. These specimens were saved for tensile testing and not sectioned. Any deviation in surface structure that coincided with acceleration changes was cause for further investigation.

Representative data plots showing the acceleration, laser power and position for the above specimens are collected in the Figures 27 to 30. It is from this information that we determine where on the specimen the g-levels change. For welding to occur, both translation and laser power has to be in the proper range and non-zero.

## 7.5 HEAT FLOW CALCULATIONS

Heat flow calculations were made to compare material and geometrical properties. Since laser welding was performed on thin sheets, and power densities were not capable of generating keyholes, the simple point source/conduction limited analytical model could be used. Constants and equations were implemented with MathCad.

The calculations show the temperature profile from the source to the edge of the metal at the surface. The trial and error method permitted the wattage to make the weld pool to be found. For the conditions of our system with 0.005" thick 304

## FIGURE 27

LASER WELD T 3 9 S1

MARCH SAMPLE, 37 A

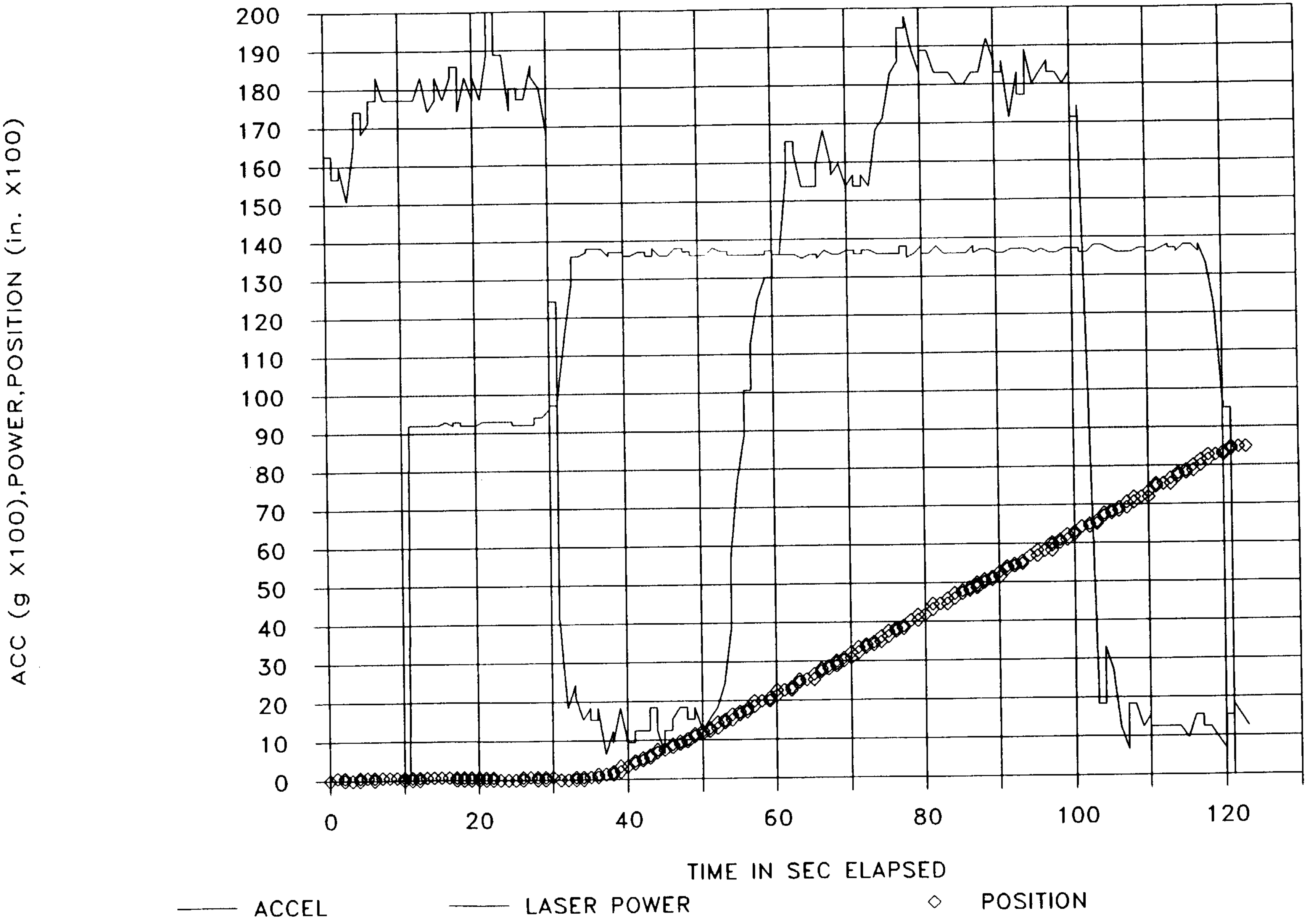
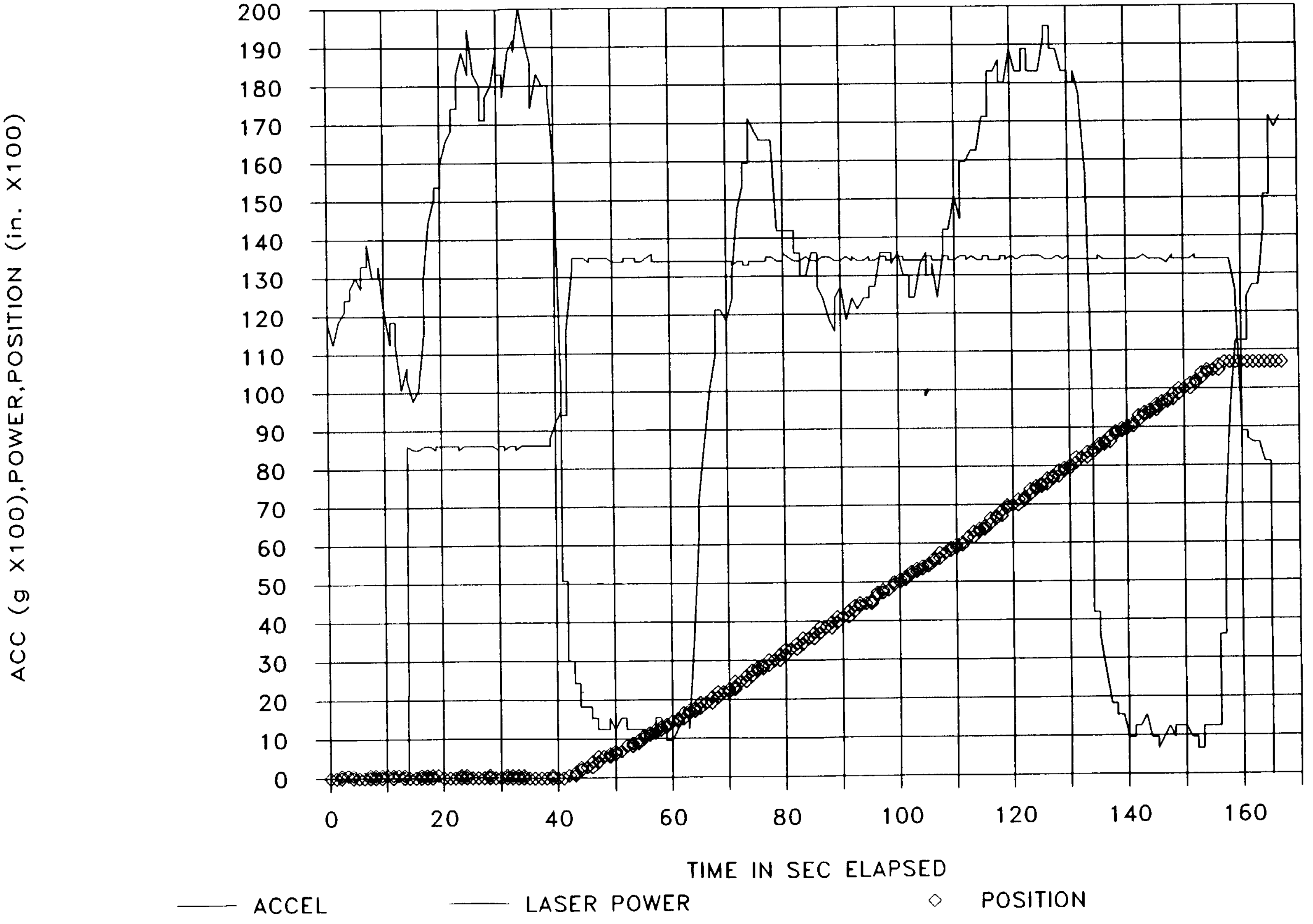


FIGURE 28

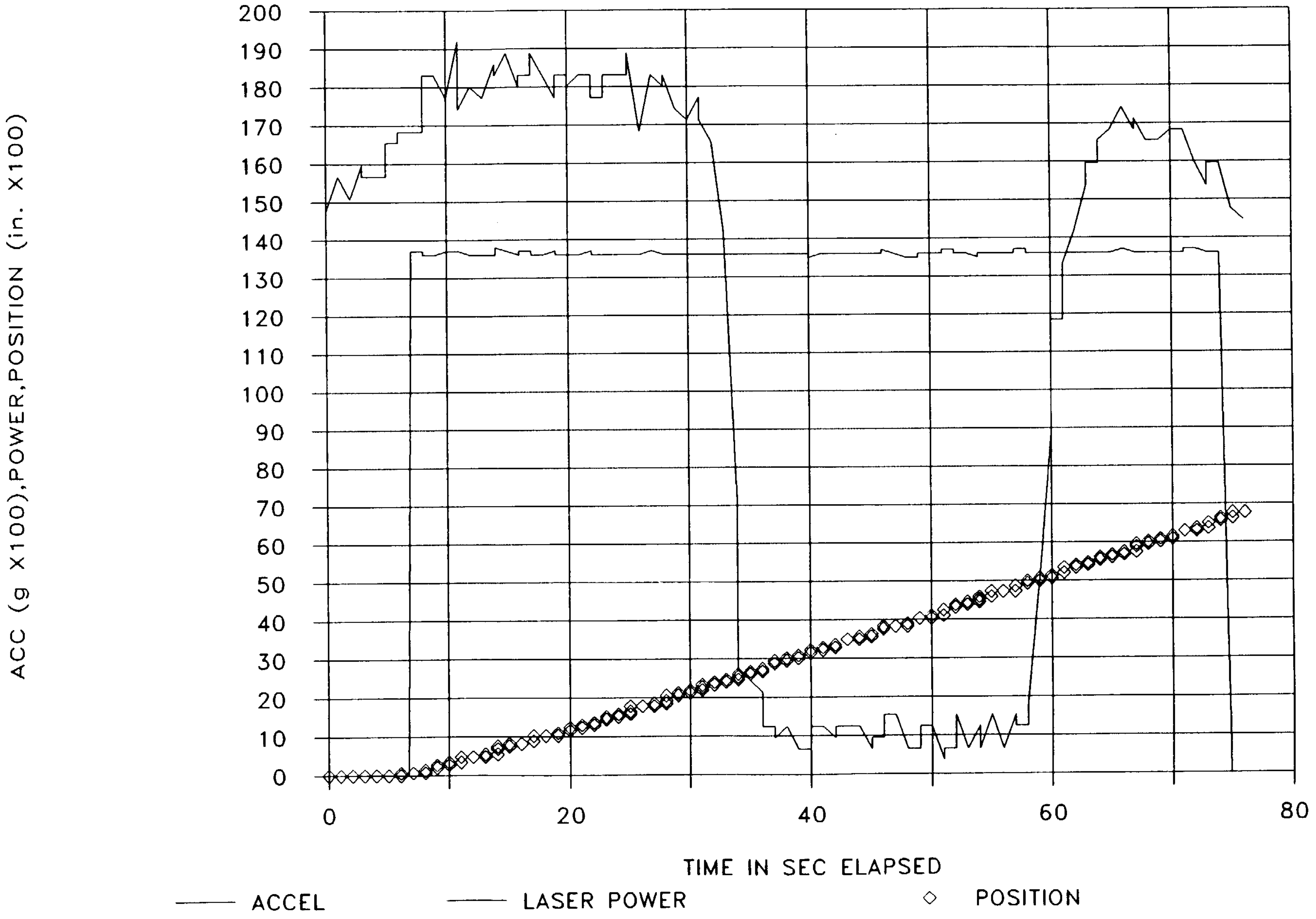
LASER WELD T 3 10 S1

MARCH SAMPLE, 37 A



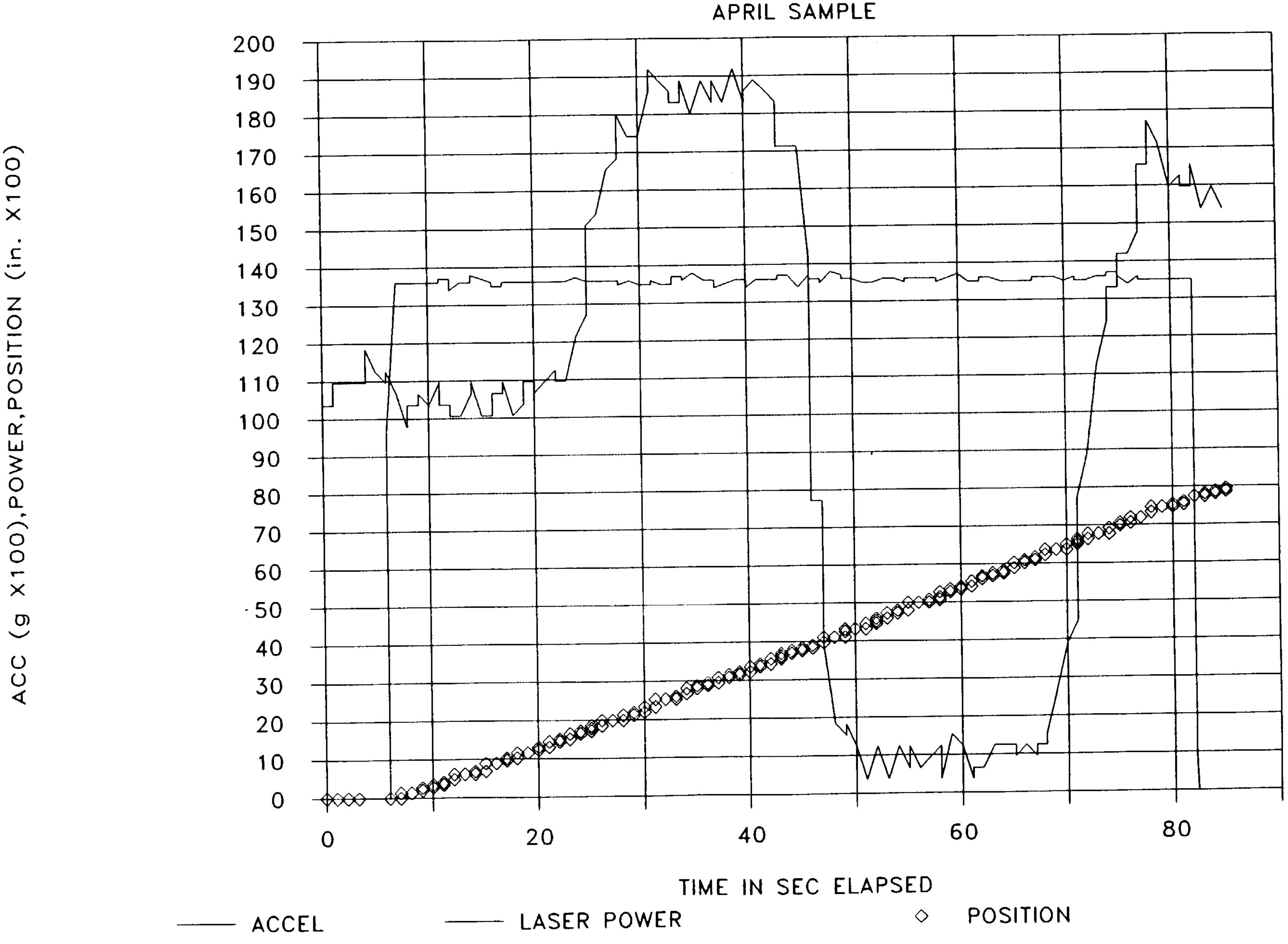
# FIGURE 29
## LASER WELD T46S2

APRIL SAMPLE



# FIGURE 30

## LASER WELD T46S3



SS, three watts of heat was needed. If aluminum were used, 12 watts would be needed. This difference is due to the high thermal conductivity of the aluminum. When a 0.07" thick aluminum Space Station strut model was used, 170 watts of power was needed to weld. All these calculations assume conduction only for heat transfer. If one should pulse the heat in a short period of time, the heat would not have sufficient time to be conducted away and the local temperature would be much higher. A detailed discussion of penetration and heat flow can be found in Section 1.

A comparison can be made of the thermal profile calculated for the same thickness of Al and SS. Figure 31 shows the result from these calculations.

A second set of calculations were made to determine the heat requirements to make a weld bead. After all the thermal data was collected, calculations showed:

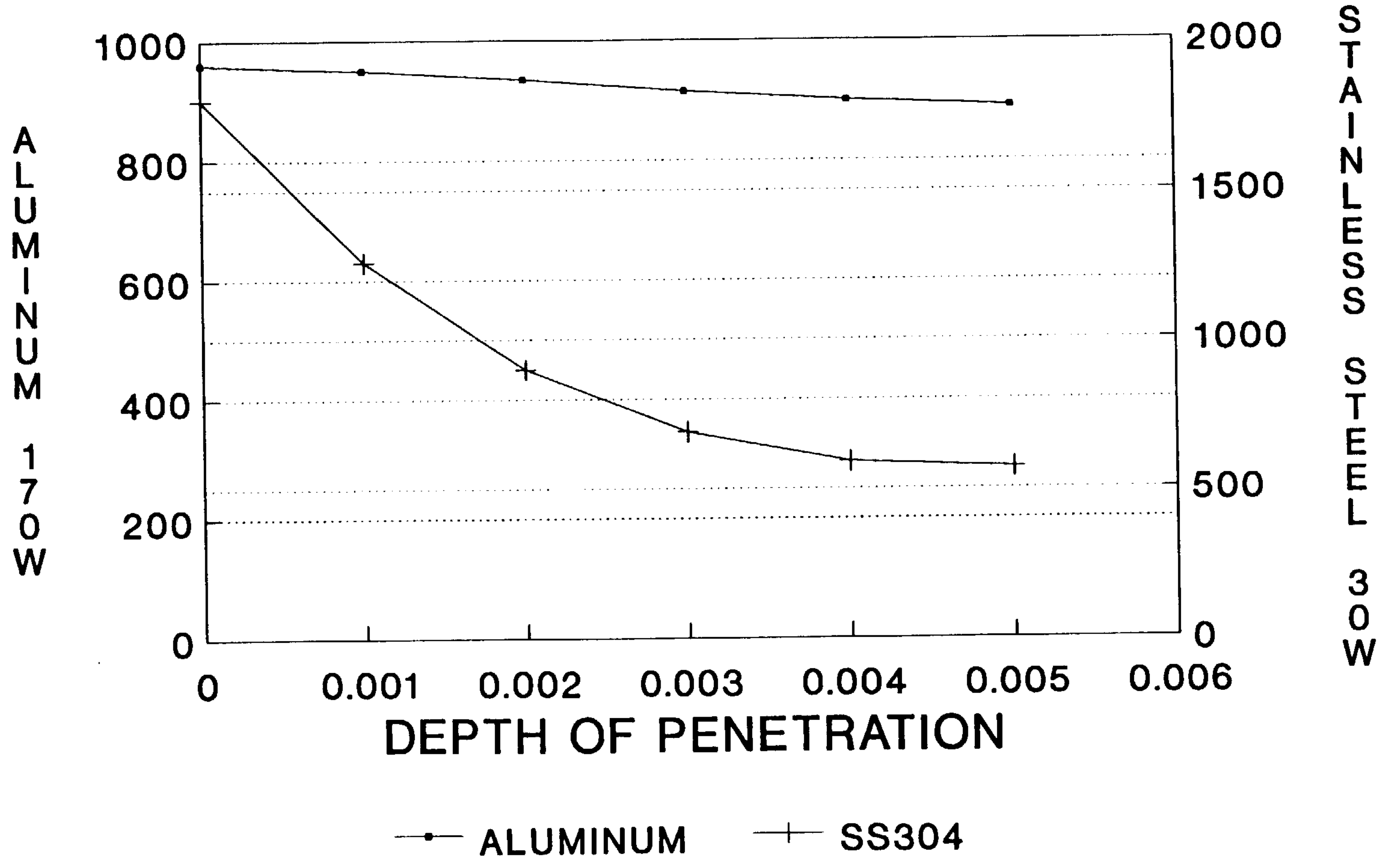
1) $1.459 \times 10^{-6}$ moles of SS constitutes a typical weld pool.
2) 183 cal of heat are needed to bring the metal in the weld pool up the melting point from room temperature.
3) It takes 0.005 cal of heat to melt the metal at the melting point for the volume above.
4) It takes 766 watt-sec of heat to do 2 and 3.

## 7.6 ANALYSIS OF MICROHARDNESS RESULTS

Microhardness profiles of transverse sections were measured. A diamond pyramid was used as the indenter and hardness readings taken along the midline of the sectioned specimen at intervals of 200-250 micrometers. At least one indentation was made in the

## FIGURE 31

## COMPARISON OF DEPTHS OF PENETRATION FOR LASER WELDING AL AND SS304



fusion zone and this point was used to center the plots. The position is in millimeters on a 50X micrograph. Hardness reading were taken from polished surfaces after metallography was performed. Conclusions are based on the ten hardness profiles for specimens with full penetration. Another dozen profile measurements were made from partial penetration welds, but there was no consistent pattern. Note that the inherent asymmetry of the weld caused an asymmetry in the profile.

Based on the accumulated results, the HAZ is represented by a one millimeter region on either side of the fusion zone which is only a third of a millimeter wide. The softest portion of the HAZ is the region adjacent to the fusion zone and has a hardness range of 150-200 DPH. This amounts to a tensile strength of 85 ksi as taken from the graph of Figure 32. ( from ASM Metals Handbook, vol 1. eighth edition) The parent metal hardness ranges between 400 and 450 DPH or around 200 ksi. All the specimens were cut from rolled sheets and welded in the highly cold worked, as-received condition. This accounts for the large drop in hardness from the parent metal to the fusion zone. Recrystallization in the HAZ raised the grain size above that in the fusion zone. As a result, the fusion zone hardness is significantly greater than the surrounding HAZ. By welding in a conduction limited regime, the HAZ is wider than it would be if higher power were available.

Two significant conclusions about the gravity level on laser welds can be made from comparing the plots. Low gravity welds have both higher hardness in the fusion zone and generate a

FIGURE 32

MICROHARDNESS CONVERSION

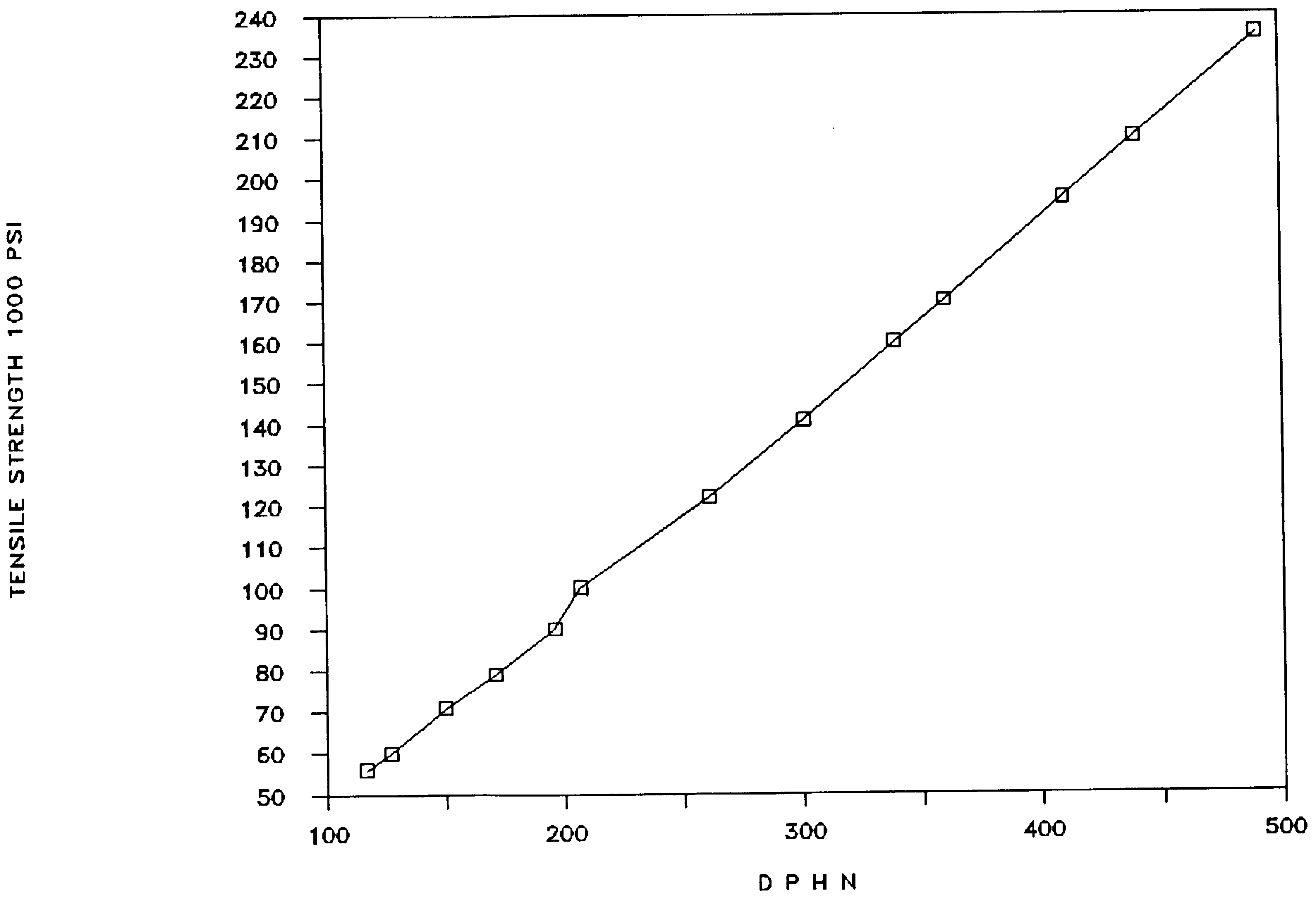


FIGURE 33

MICROHARDNESS PROFILE

T46S2 LOW G END

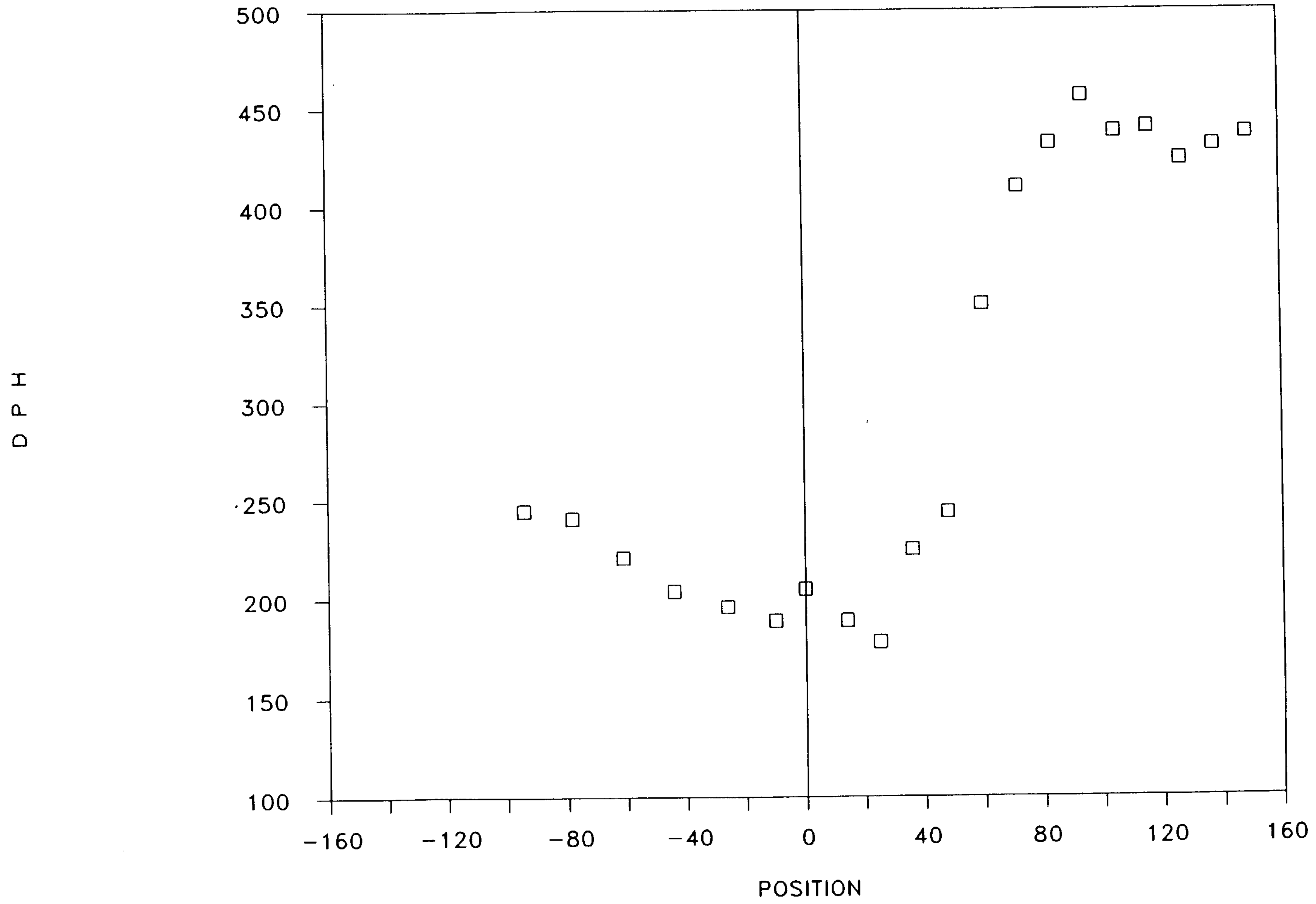
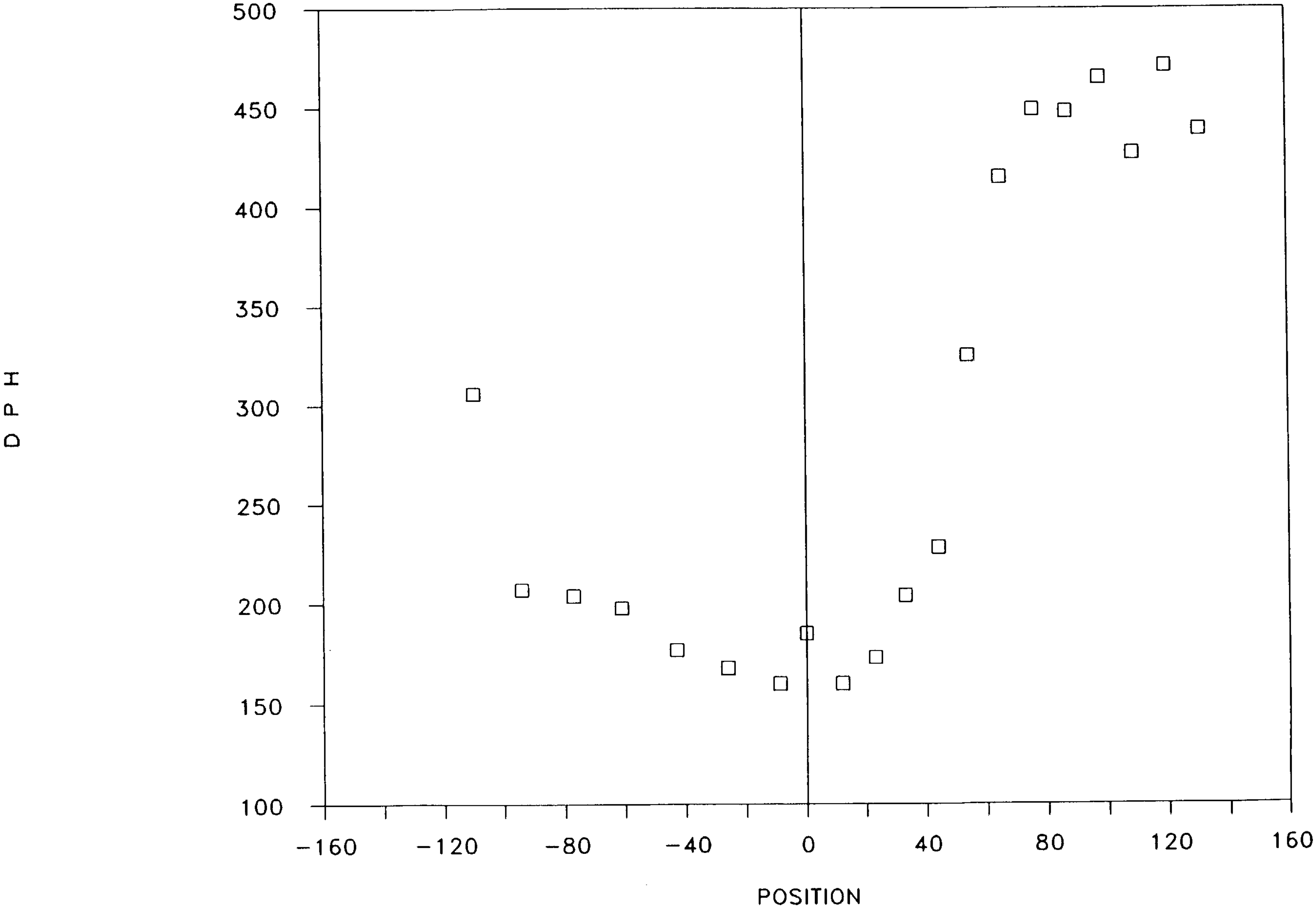


FIGURE 34

MICROHARDNESS PROFILE

T46S2 HIGH G END



narrower HAZ. One such hardness profile (of the ten available) is shown in Figure 33. These effects are both consequences of the reduction in convective flow in the low g portions. Another item of evidence that higher flow rates are found in the high g portions can be seen from the comparison of the relative difference in hardness of the fusion zone and its adjacent HAZ. In most cases, the HAZ is softer in the high g welds. A matching high g hardness profile for the same specimen as Figure 33 is shown in Figure 34. The fusion zone is however much harder with respect to its HAZ in the high g welds than the fusion zone increase in hardness over the low g weld HAZ. Higher convection rates in the high g welds causes the weld pool to be more isothermal and as a result, grain multiplication mechanisms are more likely to generate the finer and more equiaxed microstructures. More efficient heat transfer in the high g portion gave more time for grain growth in the HAZ. This could account for the lower overall hardness of the high g HAZ.

## 7.7 WELD FERRITE IN AUSTENITIC STEEL

Regardless of the welding method, the weld bead of an austenitic stainless steel will have a duplex structure of º-ferrite and austenite. Large amounts of º-ferrite will reduce the weld ductility and toughness. Some is needed to give strength to the weld during solidification and prevent cracking.

It is the initial composition of the metal that mostly determines the amount of austenite actually found in the weld. Ferrite forming constituents are Cr, Mo, Si and Cb. The total portions of these elements in 304SS add up to 21%. This is a chromium equivalent. The austenite stabilizers are Ni, C, Mn, and N. In 304SS, these amount to 13% and represent the nickel equivalent. One can predict how much º-ferrite will form by finding the intersection of the Ni and Cr equivalent values on either a Schaeffler or Delong diagram[20]. The Delong diagram includes the strong effect of N in ferrite formation. Based on the constitution of 304SS, the Schaeffler diagram predicts 8% and the Delong predicts 11% º-ferrite in the weld.

Due to the proportion of ferrite seen in the micro-structures, the higher estimate from Delong seems more reasonable. Ferrite etches dark on the microstucture and would account in part, for the higher hardness in the fusion zone. It is the distribution of ferrite in the austenite that delineates the differences in microstructure we observe between high and low g segments.

## 8.0 OUTLINE FOR FLIGHT DEVELOPMENT

### 8.1 Final Design Considerations

a.) Purchase diode pumped Nd-YAG Laser and fiber optic components to establish welding capabilities in present KC-135 experiemnt apparatus.

b.) Fly package on KC-135 to demonstrate proof of concept and specifications for diode pumped laser.

c.) Survey potential user community to determine optimal specifications for broad based research.

d.) Finalize experiment specifications and safety issues

8.2 Finalize Design and Begin Construction

a.) Procurements

b.) Fabrication

c.) Test and qualification procedures.

d.) Work with other scientific investigators for specific samples for Shuttle flight.

8.3 Obtain manifest to fly

8.4 Prepare Laser Welding Experiment and samples for flight.

## 9.0 INITIAL ASSESSMENT OF DEVELOPMENT COSTS AND SCHEDULE

The cost estimates and schedules required for performing laser welding in a Hitchhiker-g platform are presented in this section. Several assumptions are still required for assessing the actual hardware costs. As described in Section 6, the use of a diode pumped Nd-YAG laser is the obvious choice for a space experiment. Our work with the flash-lamp pumped Nd-YAG laser on the KC-135 demonstrated that the space experiment is highly desirable; however, the weld parameters will not be the same in the system proposed for Space. To operate the diode-pumped laser in pulsed mode requires determining new weld parameters for that mode of operation. For that reason, it is necessary to continue the KC-135 experiments. The preliminary work is also an extension of the previous work with an emphasis on improving experimental conditions. For instance the deficiencies in the sample chamber design need to be corrected by adding on-line vacuum pumping capability during parabolic manuevers and imaging of the weld bead during welding needs to be improved. These ground-based experiments are essential for the design of the Space experiment.

The anticipated costs and man-hours are:

| | FY91 | FY92 | FY93 | FY94 |
|---|---|---|---|---|
| Man-years | 4.26 | 4.26 | 3.33 | 1.79 |
| Labor | 140.8 | 146.7 | 70.1 | 58.1 |
| Equipment & Supplies | 115.6 | 151.4 | 15.5 | 15.7 |
| Indirect Costs (excludes equipment) | 69 | 71.7 | 32.7 | 27.6 |
| Sub-totals | 325.4 | 369.8 | 118.3 | 101.4 |
| Total man-years | 13.64 | | | |
| Total cost | $ 914.9 | | | |

Note that indirect costs are only charged on labor, supplies and materials. Equipment purchases are not charged overhead. Travel expenses for several KC-135 missions are included under equipment and supplies. A single diode-pumped laser ($35K) and improvements to the sample chamber ($20K) are included in FY91 budget. We anticipate the need for two diode pumped lasers with a ganged output for the Hitchhiker-g experiment. A spare diode pump laser is optional and is included in FY92 costs.

A Space Station Welding Facility could be developed from a concentrated effort using diode pumped lasers. However, a more cost effective and expedient process would be to to develop a solar pumped welding laser in parallel with the Shuttle Flight

Experiment. A portion of the time and materials in the estimated budget is for the design and construction of a ground-based solar laser welder. This saves the time lost by waiting for the Shuttle results before designing the solar laser and provides the opportunity to develop a flight qualified device as the follow-on step. While both welding and solar pumping a laser are certainly possible to be done in space, the capability for either is not presently available. A laser for welding has different requirements from those used for communications, ranging, or scanning. The requirements of laser welding in space will drive the solar pumped laser welder development.

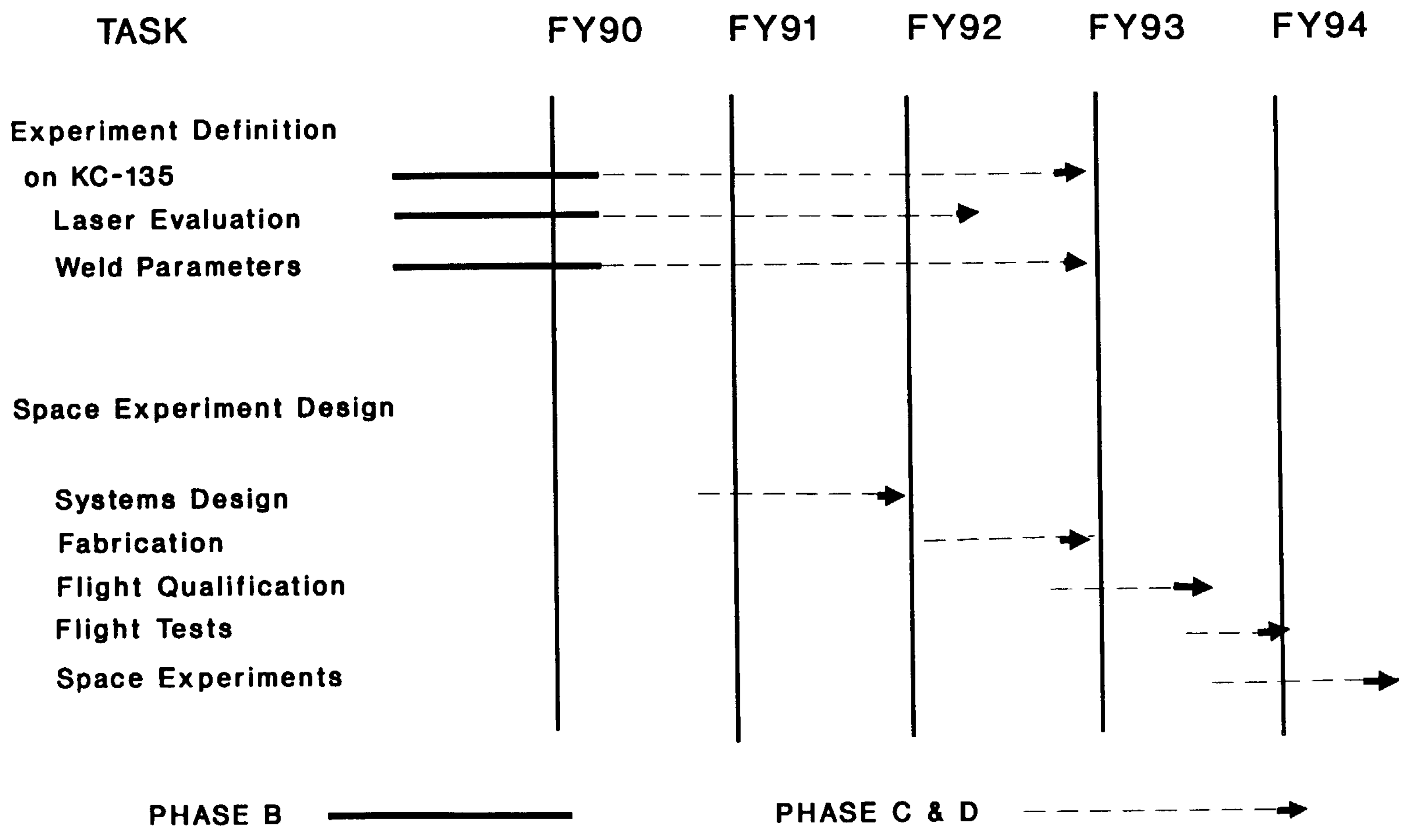
The schedule which we anticipate following is given in Figure 35.

## 10.0 SOLAR PUMPED LASERS

Welding with a laser has been shown to have clear advantages in a space environment. To power such a laser is not a trivial problem given the limited electrical power anticipated for Space Station or on the Shuttle. **All power** on Space Station comes from the sun. The photovoltaic arrays planned for Space Station are only 8% efficient converters of solar energy. It is not in NASA's best interest to have an inefficient process. Optical pumping efficiency can be over 10% in solid state lasers. High power lasers generally used for material processing are not as efficient converters of electrical energy as are small diode lasers (25%). Successful research has been performed in the past to directly solar pump lasers, usually solid state lasers.

# FIGURE 35

# LASER WELDING IN SPACE FLIGHT SCHEDULE



Relevant papers on this subject are found in references 21 to 40. Many pumping arrangements have been found in our research, each with advantages and disadvantages that influence implementation for a Space Based Welding Facility.

There are many approaches to solar pumping a laser. Our research has uncovered most of them. Only a few scientists have constructed a solar pumped laser. All that have tried succeded to generate a beam.

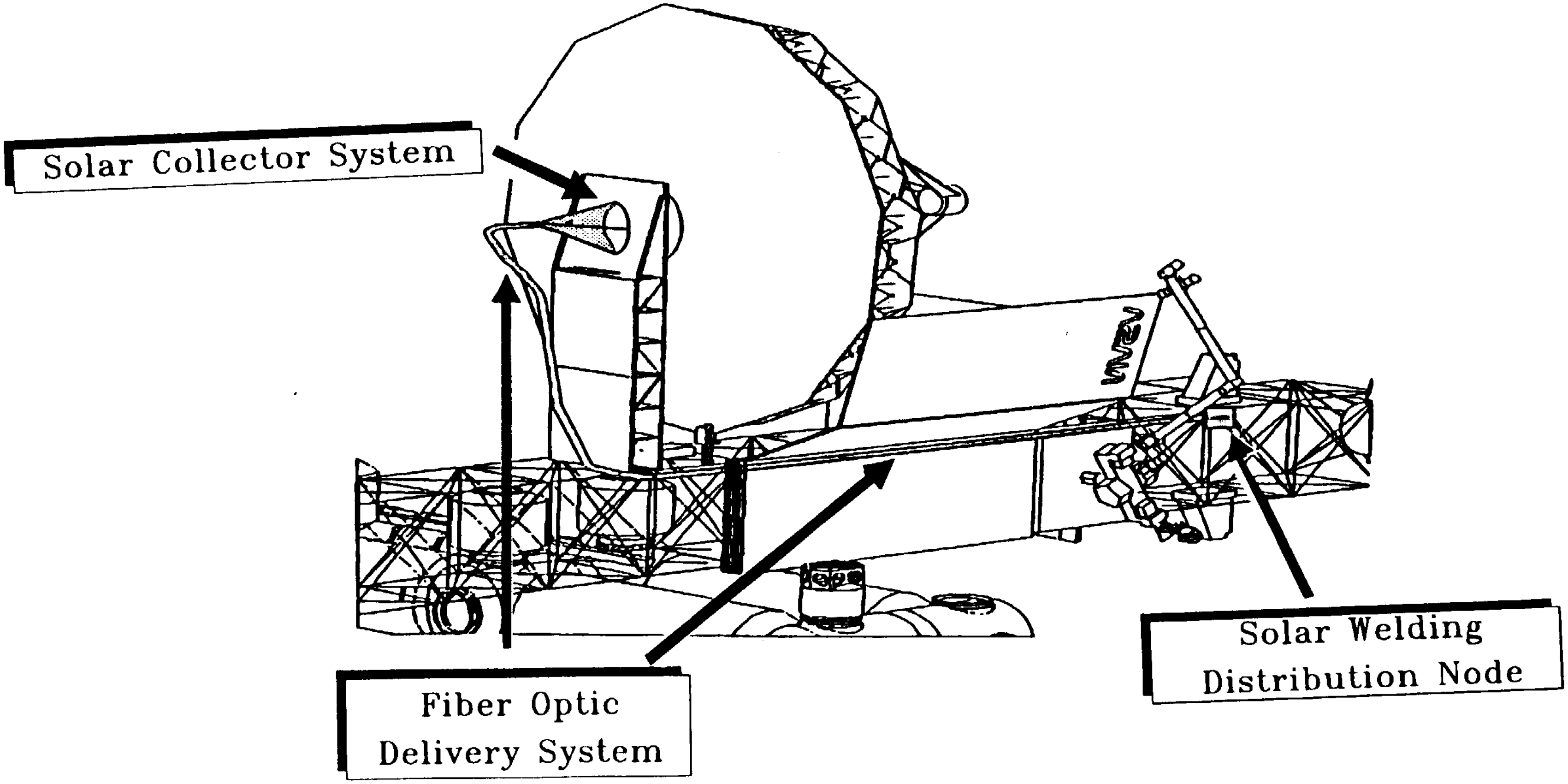
It was clear from the literature searches that much effort will need to be expended on the solitary aspect of finding the best design. How one would weld by laser is not influenced by the method of generating the beam. It is best to separate the task of laser welding in space from the solar pumped laser design. These two efforts can go in parallel. We feel in order to be prepared for Space Station, development of a solar pumped laser is needed during the next Developmental Phase. This would be performed while our Shuttle flight experiment is being prepared to evaluate salient aspects of welding by laser in space. At the end of the Developmental Phase, both a Shuttle Laser Welding Experiment and a prototype ground-based solar pumped laser for welding would be constructed. This will prepare us to fly a solar-pumped laser on another Shuttle flight that would be capable of welding. After that, recommendations could then be made to begin construction of a Laser Welding Facility for Space Station.

At this time we are in a position to offer a few alternative concepts for a Space Based Solar Pumped Laser. One concept which seems to be a rather easy implementation is the use of the Solar Dynamic Furnace type concentrator with a fiber laser at the focus. Its use as a Space Station Welding System is shown in Figure 36. Another concept that stands out as the optimal choice based on arguments of overall simplicity. In a NASA TM by Williams and Zapata[21], use of a fiber geometry for a solar pumped Nd laser was mentioned for a communications laser. A Gatling-gun mechanism was also suggested which has been adapted for our design. Problems of coherency and phase locking were described that made the concept difficult for its use as a communications device. In the case of welding, these problems can be ignored. Fiber lasers are not new technology. Operating single fiber lasers have been around for many years. While not necessarily the highest efficiency, the Multi-Fiber-Laser concept offers greatest potential for success through built-in redundancy, few moving parts, simple cooling system, ease for scale-up (to higher power) and high tolerance to pointing inaccuracies. A schematic of the concept is shown in Figure 37.

Our prototype will employ the Multi-Fiber-Laser concept. Again, simplicity for reliability is the key. Our design will have a cylindrical arrangement of Nd-YAG or glass fibers which will be rotated continuously through the axial focus of a parabolic 'trough' reflector. The output of each fiber will be collected to a common fiber for delivery to the work site. By using refractory materials for the fibers they can safely reach high temperatures. Before the temperature reaches dangerous levels, the fibers in the collector focus are revolved out of the

# FIGURE 36

## CURRENT SOLAR COLLECTOR EXPERIMENTS CAN ASSIST IN DEVELOPING SOLAR PUMPED LASER TECHNOLOGY

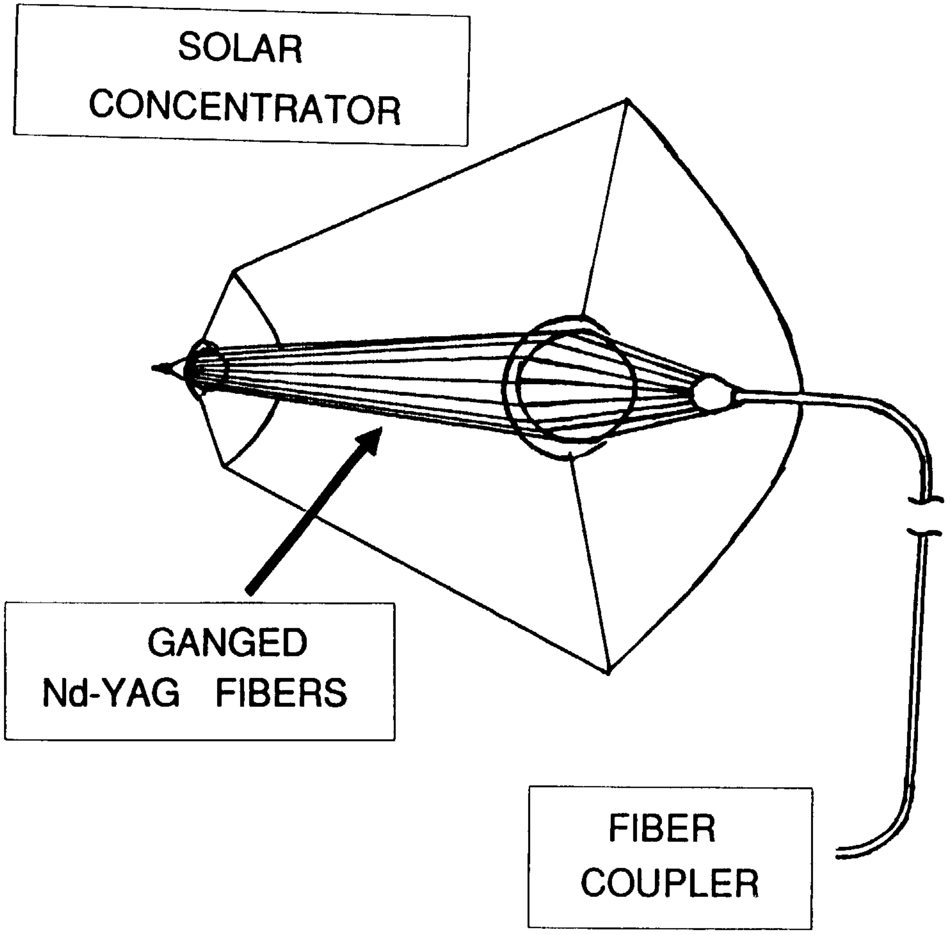

Solar Collector System
NASA
Fiber Optic Delivery System
Solar Welding Distribution Node

Current concepts being developed for the Solar Dynamics Furnace and the Large Deployable Reflector Assembly will also provide a testbed for applying solar pumped lasers to repair and/or assembly operations.

# FIGURE 37

# SOLAR ARRAY MULTI-FIBER ARRAY CONCEPT

In order to optimize laser cooling for laser fibers pumped by concentrated solar energy; a rotating ganged array of Nd-YAG fibers provide laser power at the focus of the concentrator and cool when rotated out of the pumping region.


SOLAR CONCENTRATOR
GANGED Nd-YAG FIBERS
FIBER COUPLER

focus to radiatively cool to space. New fibers are continuously being brought into focus to lase while others are being removed to cool. "Power per fiber (10 micrometer diameter) is limited by stimulated Raman and brillouin scattering."[21]

Solar pumping a laser terrestialy as opposed to in space requires different approaches. On the ground, one can devise schemes for high concentration ratios to deliver large powers but actively cool with a large circulating water system. In Space, cooling or removing unwanted heat is a major problem. Lower concentration ratios can be used to reduce cooling requirements. Larger, lightweight structures are easily deployed in the microgravity environment of space. Radiative cooling is the only means to remove heat in space. By allowing a material to reach higher temperatures, radiation losses are much greater and cooling more efficient. Radiative heat rejection at the low temperatures obtained by active cooling is very inefficient and would require a massive radiator and coolant volume. Electrical power to pump a coolant is not required. In order to control the output and prevent interference between the lasers, each fiber will be Q-switched to fire pulses idependently. Q-switching will produce better penetration by the laser and also improves the Multi-Fiber-Laser performance.

One of the other novel features of the design is that output power is increased by lengthening the cylinder of fibers and the concentrator. Simply by suspending the fibers at their ends, in the microgravity environment, there will be no sag and fiber lengthening or contraction from cyclic heating and cooling will be accomodated at the suspension points. Centrifugal force from rotation may cause the fibers to bow outward slightly. Fiber tension and rotation speed affect this. Focus depth (of the concentrator) is large and some fiber movement is tolerated. Failure of some laser fibers or reduced performance will not disable the welding facility. Pointing requirements are reduced to a simpler azimuthal control. By not requiring exceptionaly high concentration ratios, pointing precision is not as critical.

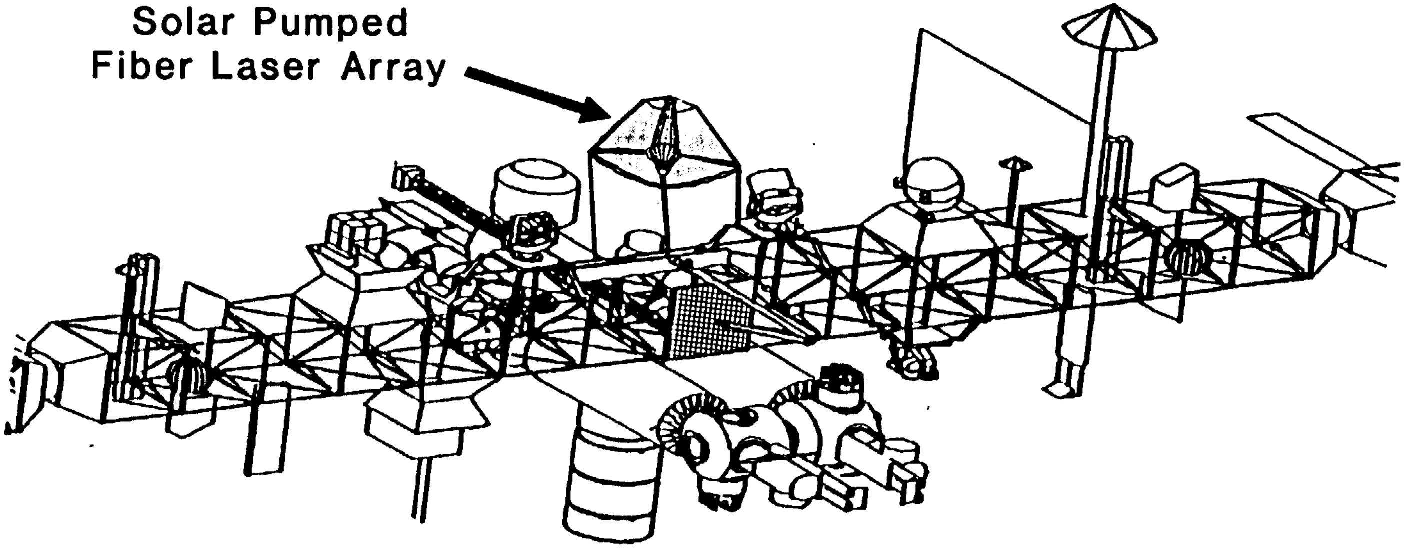
How the Solar-Laser Welder would appear mounted on the latest Space Station concept is depicted in Figure 37. By using the fiber optical delivery method, essentially only the coupling losses to the delivery fiber will be incurred. After that, whether the fiber is 5 feet long or 15 feet long, there will be little difference in output. (This last statement requires the assumption that there are no severe bends in the fiber.)

## 11.0 ACKNOWLEDGEMENTS

We wish to thank all the NASA personnel who assisted us in performing the KC-135 flights, particularly Dr. Robert Shurney from the KC-135 Flight Office at MSFC, Robert Williams, the Flight Test Director for the KC-135 flights at JSC, and Jay Bennett, the technical contract monitor at JSC. Others who made significant contributions include Teresa Plaster and the students workers at UAH. In particular we wish to thank Bill Smith, Jeff Haight and Robert Bond for putting in a lot of effort on this project and Christine von Pragenau for assisting in the report preparation.

# FIGURE 38

## ARRAY OF SOLAR PUMPED LASER FIBERS PROVIDES LASER WELDING POWER FOR SPACE STATION



A rotating array of Nd-Yag fibers provides the conceptual foundation for solar pumped laser welding facilities for space operations demanding large power requirements, such as Space Station assembly and repair. The laser energy for welding is delivered to the end effector of the robot from the solar pointing collector through a multipurpose fiber optic bus.

## 11.0 REFERENCES

1. Anthony, T.E. and H.E. Cline, (Sept. 1987) J. App. Phys. **48**, 3888.

2. Strutt, P.R., B.G. Lewis, and B.H. Kear, **Rapidly Solidified Amorphous and Crystalline Alloys**, Elsevier, 1982, pp 485-498.

3. Chan C., J. Mazumder, and M.M. Chen, (Dec. 1984.) Met Trans ISA: 2175.

4. Heiple, C.R. and P. Burgardt, (1985) Weld J. **64** 159s.

5. Lin, M. L. and T. W. Eagar, (18-22 May 1986) **Advances in Welding Science and Technology**, Proceedings, ASM, pp 47-51.

6. Kou, S. and D.K. Sun, Metall. Trans. **16A** (1985) 203.

7. Heiple, C.R., P. Burgardt, and J.R. Roper, (18-22 May 1986) **Advances in Welding Science and Technology**, Proceedings, ASM, pp 387-392.

8. Zacharia, T., A.H. Eraslan, and D.K. Aidun, (Mar. 1988) Welding Res. Sup., pp 53s-62s.

9. Zacharia, T., A.H. Eraslan, and D.K. Aidun, (1988) **Modeling and Control of Casting and Welding Processes IV**, The Minerals Metals and Materials Soc., pp 177-188.

10. McKannen, E.C. and R.M. Poorman, "**Skylab M551 Metals Melting Experiment**", Proceedings of Third Space Processing Symposium: Skylab Results, NASA Publication M-74-5, 1974, pp 85-100.

11. Ireland, C.L.M., Laser Focus, November, 1988, pp 49-64.

12. Paton, B.Y., D.A. Dudko, and V.F. Laphinskiy, "**Welding Processes in Outer Space**", USSR Report, Materials Science and Metallurgy, JPRS-UMS-8S-08, pp 121-129, translated by Foreign Broadcast Information Service.

13. Allario, F., Laser Focus, October, 1988, pp 65-74.

14. Lesh, J.R. and M.D. Rayman, Laser Focus/Electro-optics, October, 1988, pp 81-86.

15. Begley, D. and B. Boscha, Photonics Spectra, August, 1989, pp 81-82.

16. Cohen, M.I., "**Material Processing**", published in Laser Handbook, vol. 2, ed. Arecchi and Schulz-DuBois, North Holland, Amsterdam, 1972 PP 1577 - 1648.

17. Irving, R.R., The Iron Age, (1965) p 81

18. Mueller, R.E., W.W. Duley, et. al., Jour. Laser Appl. **1** (3) , (1989) pp 22-25.

19. Rosenblum, Welding Jour., 1941

20. Koo, Sindo, **Welding Metallurgy**, John Wiley & Sons, N.Y ,1987

21. Williams, M.D., and L. Zapata, **"Solar-Pumped Solid State Nd Lasers"**, NASA Technical Memorandum 87615, Langley Research Center, 1985, pp. 1-18.

22. Williams, Michael D., **"Solar Power Absorption in a Glass Tube"**, NASA Technical Memorandum 89063, Scientific and Technical Info. Branch, 1987, pp. 1-12.

23. Gleckman, Philip, **"Achievement of Ultrahigh Solar Concentration with Potential for Efficient Laser Pumping"**,Applied Optics, Vol. **27**, No. 21, 1988, pp. 4385-4391.

24. Ross, Monte, Paul Freedman, James Abernathy, George Matassov, John Wolf, and James D. Barry,**"Space Optical Communications with the Nd: YAG Laser"**,Proceedings of the IEEE, Vol. 66, No. **3**, 1978, pp. 319-343.

25. Arashi, H., Y. Oka, and M. Ishigame,**"A Solar-Pumped Laser on the Space Station"**,Space Solar Power Review, Vol. **5**, 1985, pp. 131-133.

26. Weksler, M., and J. Shwartz, **"Solar-Pumped Solid-State Lasers"**, IEEE Journal of Quantum Electronics, Vol. **24**, No. 6, 1988, pp. 1222-1228.

27. Arashi, Haruo, Yasuo Oka, Nenokichi Sasahara, Atsushi Kaimai, and Mareo Ishigame, **"A Solar-Pumped cw 18 W Nd: YAG Laser"**, Japanese Journal of Applied Physics, Vol. **23**, No. 8, 1984, pp. 1051-1053.

28. **"Highly Concentrated Sunlight Opens Way To Many New Applications"**,Research and Development, 1988, p. 58.

29. Nath, G., **"Hand-Held Laser Welding of Metals Using Fibre Optics"**, Optics and Laser Technology, 1974, pp. 233-235.

30. Young, C.G., **"A Sun-Pumped cw One-Watt Laser"**, Applied Optics, Vol. **5**, No. 6, 1966, pp. 993-998.

31. Zittel, Werner, **"Design Studies for a Solar Pumped Laser Device"**, Deutsch Forschungs-und Versuchsanstalt fur Luft-und Raumfahrt, 1988, pp. 4-58.

32. Harries, Wynford L., and Zeng-Shevan Fong, **"Theoretical Studies of Solar-Pumped Lasers"**, Technical Report PTR 85-2, 1985, pp. 1-3.

33. Golger, A.L., I.I. Klimovsky, **"Solar-Pumped Lasers"**, Institute of High Temperatures, USSR Academy of Sciences, pp. 686-693.

34. De Young, R.J., G.D. Walberg, E.J. Conway, and L.W. Jones, **"A NASA High-Powered Space-Based Laser Research and Applications Program"**, NASA Scientific and Technical Information Branch, 1983, pp. 1-40.

35. Lazerev, V.V., and V. Ya. Panchenko, **"Spectral Transformation of the Sun's Radiation Using a Body Heated by it as the Means of Pumping Gas Lasers"**, Geliotekhnika, Vol. **22**, No. 1, pp. 3-8,1986, (Allerton Press, 1986, pp. 1-7).

36. Harries, W.L., **"Criteria for the Evaluation of Laser Solar Energy Converter Systems"**, Technical Note, American Institute of Aeronautics and Astronautics, 1985, pp. 411-413.

37. Golger, A.L., and I.I. Klimovskii, **"Lasers Pumped by Solar Radiation (Review)"**, American Institute of Physics, 1984, pp. 164-179.

38. Young, R.J., and E.J. Conway, **"Progress in Solar-Pumped Laser Research"**, NASA Langley Research Center, pp. 467-482.

39. Young, R.J., G.H. Walker, M.D. Williams, G.L. Schuster, and E.J. Conway, **"Preliminary Design and Cost of a 1-Megawatt Solar-Pumped Iodide Laser Space-to-Space Transmission Station"**, NASA Technical Memorandum 4002, 1987, pp. 1-19.

40. DeYoung, R.J., J.H. Lee, M.D. Williams, G. Schuster, and E.J. Conway, **"One-Megawatt Solar Pumped and Electrically Driven Lasers for Space Power Transmission"**,

## ADDITIONAL REFERENCES USED IN THIS WORK

1. The Physics of Welding, 2nd ed. Ed. J.F. Lancaster, Pergomon Press, 1986.

2. Carrupt, B., M. Rappaz, and M. Zimmerman, **"Modeling of Microstructure Formation in Laser Treatment of Materials"**, Modeling of Casting & Welding Processes IV, 1988, pp. 581-591.

3. Handbook of Solid-State Lasers, Ed. Peter K. Cheo, Marcel Dekker Inc.,1989.

4. Eloy, Jean-Francois, Power Lasers, Halsed Press-Ellis Horwood Limited, 1987.

5. Duley, W.W., CO2 Lasers\Effects & Applications, Academic Press Inc., 1976.

6. Modeling of Casting & Welding Processes II, Ed. J.A. Dantzig, J.T.Berry, Conference Proceedings, 1984.

7. Tsai, M.C., and S. Kou, **"The Advantage of Orthogonal Curvilinear Coordinates in Simulating Marangoni Convection in Deformed Weld Pools"**, Modeling of Casting & Welding Processes IV, 1988, pp. 409-420.

8. Paul, A., and T. DebRoy,**"Prediction of Marangoni Convection, Heat Transfer, and Surface Profiles during Laser Welding"**, Modeling of Casting & Welding Processes IV, 1988, pp. 421-429.

9. Zacharia, T., A.H. Eraslan, & D.K. Aidun,**"Welder: A Computer Code for Simulating Welding Processes"**, Modeling of Casting & Welding Processes IV, 1988, pp. 177-185.

10. Eraslan, Arsev H., Thomas Zacharia, Daryush K. Aidun, **"Welder: A Computer Code for Simulating Fast-Transient, Three-Dimensional, Three-Phase, Flow, Temperature & Material Composition Conditions During Welding"**, Dept. of Mechanical & Industrial Engineering, Report No. MIE-142,1986.

11. Laser Welding, Cutting, & Surface Treatment, The Welding Institute, Cambridge, England, 1984.

12. Sanderson, Ronald J., Lasers in Metalworking (Summary & Forecast), Tech. Tran Corporation, 1983.

13. Laser Photochemistry, Tunable Lasers, and Other Topics, Ed. Stephen F. Jacobs, Murray Sargent III, Marlan O. Scully, Charles T. Walker, Physics of Quantum Electronics Vol. 4, Addison-Wesley Publishing Co. Inc., 1976.

14. Mortland, J.E., R.M. Evans, & R.E. Monroe, Welding and Brazing of Nickel-Base Alloys, National Aeronautics & Space Administration, 1972.

15. Laser-Material Processing Committee, Guide to Material Processing by Lasers, Laser Institute of America, 1977.

16. Welding Design & Fabrication, Ed. Rosalie Brosilow, Penton Pub., Vol. 62, No. 6, 1989.

17. Welding Handbook, 8th ed., Vol. 1, American Welding Soiety, 1987.

18. Laser Surface Treatment of Metals, Ed. C.W. Draper and P. Mazzoldi, Martinus Nijhoff Pub., 1986.

19. Arata, Yoshiaki, Plasma, Electron, and Laser Beam Technology, American Society for Metals, 1986.

20. Laser Welding, Machining, and Materials Processing, Ed. Prof. C. Albright, IFS (Publications) Ltd, 1986.

21. Laser Measurements/Professional Adv. Course, Laser Institute of America, 1985.

22. Fundamentals of Lasers/Professional Adv. Course, Laser Institute of America, 1985.

23. Power Beam Processing/Electron, Laser, Plasma-Arc, Ed. E.A. Metzbower and D. Hauser, ASM International and the Edison Welding Institute, 1988.